ERDC/CHL TR-02-5

Coastal and Hydraulics Laboratory

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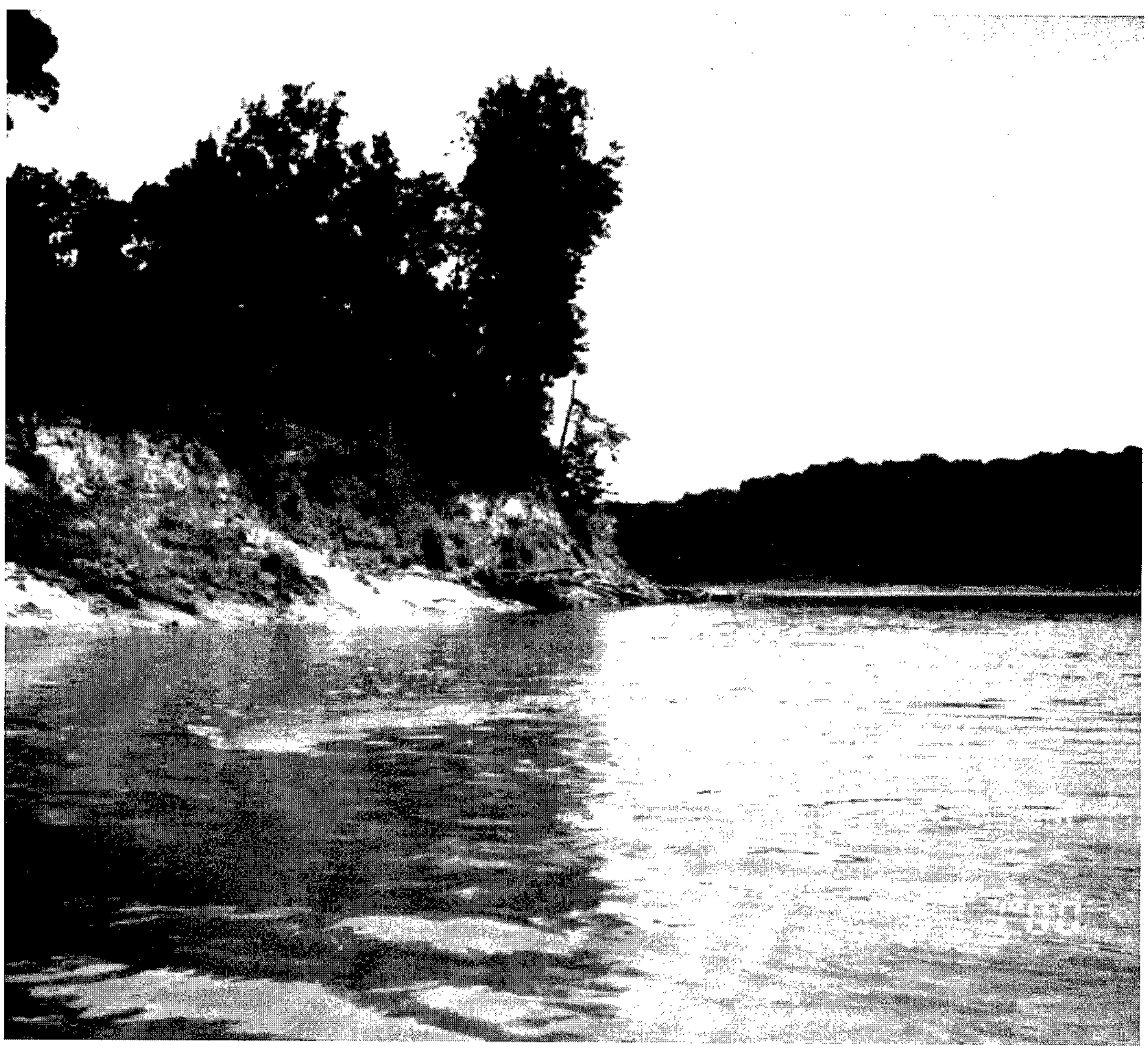
Red River Below Denison Dam, Texas, Oklahoma, Arkansas, and Louisiana

Numerical Sedimentation Model Study

Ronald R. Copeland

May 2002



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Numerical Sedimentation Model Study

by Ronald R. Copeland

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Final report

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Tulsa, OK 74128

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Preface

This sedimentation study for the Red River between Denison Dam and Lock and Dam No. 5, was conducted at the Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS, of the U.S. Army Engineer Research and Development Center (ERDC) at the request of the U.S. Army Engineer District, Tulsa.

This investigation was conducted during the period January 2000 to November 2001 under the direction of Mr. Thomas W. Richardson, Acting Director of CHL, Mr. Thomas J. Pokrefke, Acting Deputy Director of CHL, Dr. Yen-Hsi Chu, former Chief of the River Sedimentation Branch, CHL, and Mr. James Leech, current Chief of the River Sedimentation Branch, CHL. The principal investigator was Dr. Ronald R. Copeland, CHL.

During the course of this study, close working contact was maintained among engineers at the Tulsa District and ERDC. The project engineer at the Tulsa District was Mr. Phillip Cline. Independent technical review was provided during the conduct of the study by Messrs. Fred Pinkard, Rick Robertson, and Larry Banks of the U.S. Army Engineer District, Vicksburg. This report was prepared by Dr. Copeland.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	0.40469	hectares
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1.609357	kilometers
square mile	2.5890	square kilometers
U.S. ton	0.9091	tonne

1 Introduction

Background

The headwaters of the Red River are in the Llano Estacado of eastern New Mexico. The river follows an easterly course across the Texas panhandle, through southern Oklahoma, forms the boundary between Oklahoma and Texas, runs through southwestern Arkansas, abruptly turns south and runs through northwest Louisiana, ending at Old River at its confluence with the Atchafalaya River. The Red River basin has a drainage area of about 93,244 square miles at the mouth of the Lower Old River Navigation Channel. Denison Dam, near Denison, TX, controls the upper 39,720 square miles. A location map and a map showing project features are shown in Figure 1.

The Red River is about 1,000 miles long. The lower 530 miles of the river, below Denison Dam, flow through a valley filled with alluvium which grades downward from red clay at the surface through red silt, brown and gray sand to gravel, encountered at 60 to 95 ft. However, generally the riverbed does not encounter the lower coarse sand or gravel, thus limiting its ability to armor its bed during degradation. However, local lenses of gravel may exist and provide sufficient coarse sediment for a local armor. Since the mid-1800s the major land use along the Red River has been and still is agricultural. There are no obvious bedrock controls.

The Red River Waterway Project was authorized in 1968 and to date consists of five locks and dams between Marksville, LA, and Shreveport, LA, many channel realignments, dikes, and areas of bank stabilization. The waterway was renamed and dedicated as the J. Bennett Johnston Waterway in 2000. The Red River is a heavily sediment laden stream. The suspended sediment load per square mile of drainage area on the Red River is one of the highest of all navigable rivers within the United States. The Red River is also a high-energy system characterized by high channel velocities. During high water, mean channel velocities often approach 7 ft/sec with maximum velocities exceeding 10 ft/sec. The banks of the lower Red River generally consist of fine sand and silt. The combination of high channel velocities and easily erodible banks results in very active bank caving. Lateral migration of several hundred feet of bank line during a single high-water event is not uncommon (Pinkard and Stewart 2001).

Previous studies for the Tulsa District used as background for this study include a geomorphic study conducted by Harvey et al. (1987), and a sediment transport study completed in 1998 (USAED, Tulsa, 1998). The 1998 study used a

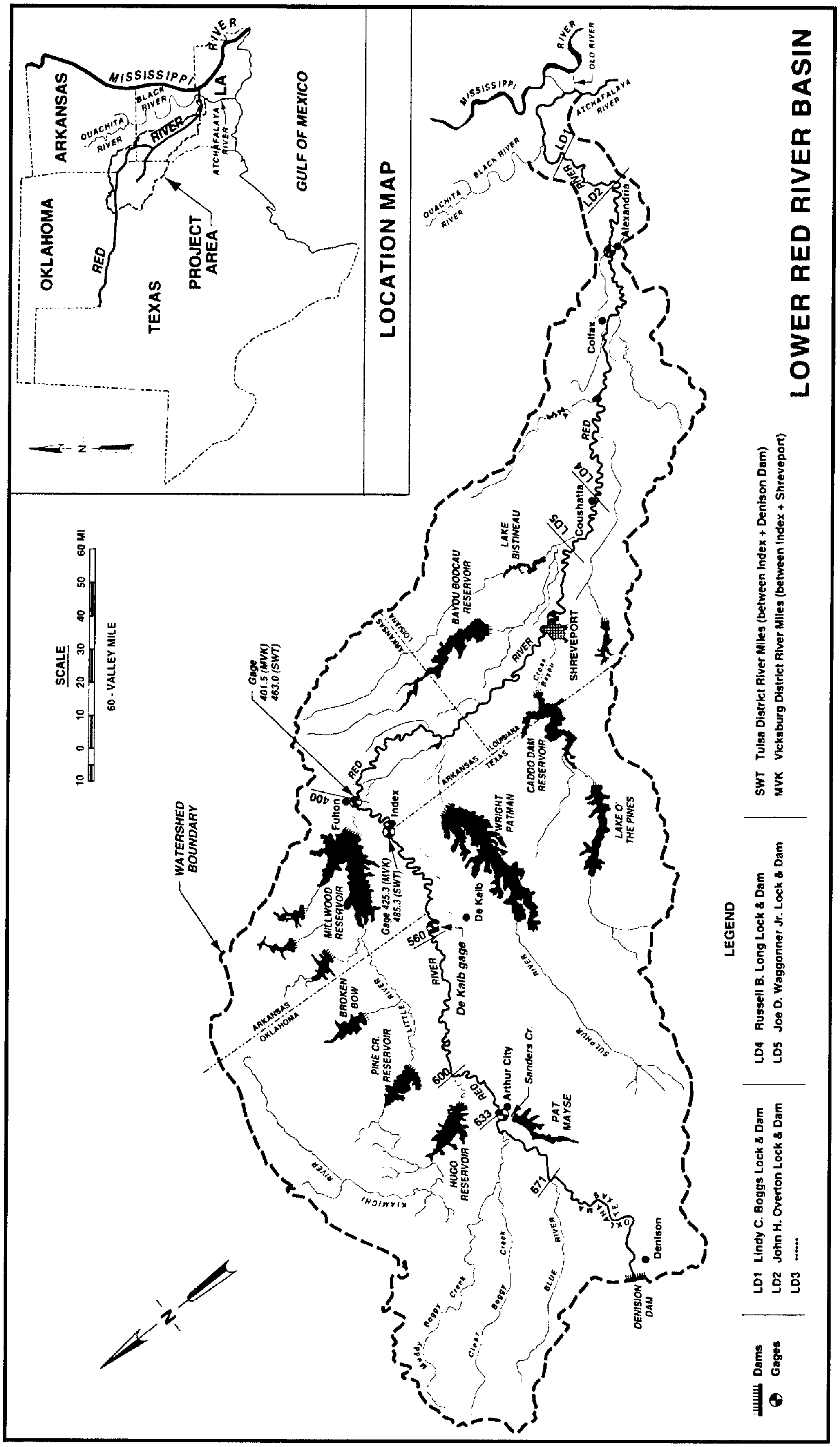

Figure 1. Lower Red River basin

sediment budget approach to approximate sand deposition upstream from Lock and Dam No. 5. In addition, a numerical model sedimentation study completed for the Vicksburg District by Simons, Li and Associates (1988), was used to develop the numerical model for this study.

Purpose of Numerical Model Study

The objective of this study was to predict the effect that reducing bank erosion between Arthur City, TX, and Index, AR, would have on deposition rates in the J. Bennett Johnston (Red River) Waterway. This was accomplished by evaluating measured sediment data and by using the HEC-6W numerical sedimentation model to simulate the complex physical sedimentation processes that govern sediment transport. A detailed model that identified aggradation and degradation reaches upstream from Index was not required. Due to limited resources, the study was conducted using available data.

The advantage of the numerical model approach over the sediment budget approach used in previous studies is that all the sedimentation processes–erosion, entrainment, transport, deposition, and compaction–are accounted for in the model. Continuity of sediment by size class is maintained in the numerical model in both spatial and temporal domains. For example, changes in sediment transport capacity with aggradation and/or degradation over time is accounted for. Changes in sediment transport with changes in sediment concentration due to relatively clear inflow from tributaries and large influxes of sediment from bank erosion are accounted for. Response of the river's bed gradation to the variation in the natural hydrograph is accounted for.

Study Approach

The HEC-6W model was developed to simulate the Red River between Lock and Dam No. 5 and Arthur City. Geometry for the model came from available survey data and existing numerical models. Sediment inflow at the upstream boundary was based on measured sediment data. Channel degradation was calculated using the numerical model. The adjusted numerical model was used to evaluate the effect of reducing bank erosion on deposition in the Red River Waterway. Two conditions were evaluated. Bank erosion was reduced by 50 percent, and bank erosion was eliminated.

Basically three sources supply sediment to the waterway. These are watershed erosion, which is delivered to the river by tributaries; channel bank erosion; and channel degradation. In this study, sediment delivered by tributaries was neglected because reservoirs capture most of the sediment load generated off of the watersheds. This is consistent with assumptions made in previous studies (Harvey et al. 1987; Simons, Li and Associates 1988; and USAED, Tulsa, 1998). Sediment supplied by channel degradation was calculated using the numerical model. Bank erosion rates were adjusted to reproduce measured sediment transport rates.

Only existing geometric data were used in the numerical model study. Very good cross-sectional information was available from an existing HEC-6 model between Joe D. Waggonner Jr. Lock and Dam (Lock and Dam No. 5) and Index. Channel geometry in this HEC-6 model was based on the 1980-81 hydrographic survey. Very sparse 1969 degradation survey data were available between Index and Arthur City. Sparse cross-sectional data, which were based on the 1967-68 hydrographic survey, were available in an existing HEC-6W model downstream from Lock and Dam No. 5 to Lindy C. Boggs Lock and Dam (Lock and Dam No. 1). The Vicksburg District completed a hydrographic survey of the Red River from its mouth at the Lower Old River Navigation Channel to upstream of Shreveport in 1993. This survey had cross-section intervals of 500 ft. The 1993 data were not used to develop a numerical model downstream from Lock and Dam No. 5 due to study scope limits.

Suspended sediment measurements were available at Arthur City, TX, and Fulton, AR. The Arthur City and Index data had been collected between 1938 and 1977. The Fulton data were more recent, 1984-96. Some of the data at Arthur City and Fulton included size class distributions, which made it possible to accurately define the distribution of the sediment inflow to the model and to circumstantiate the model performance relative to sediment transport. The older data at Arthur City were used to determine sediment inflow at the numerical model's upstream boundary. It was assumed that watershed conditions upstream from Arthur City were not significantly different from those between 1958 and 1977.

It was determined that the coarse silt fraction constituted a significant portion of both the sediment in transport and the sediment found in the banks. In this study the transport of both medium and coarse silt was calculated using a non-cohesive transport equation in order to more reliably evaluate their deposition rates in the Red River Waterway.

The distribution of bank erosion rates between Index and Arthur City was based on eroded and deposited areas determined from a comparison of aerial photos taken in 1987 and 1996. Bank erosion rates were assumed to be proportional to the areal extent of erosion and deposition. Bank erosion quantities would be assigned so that the sediment budget between sediment inflow at Arthur City and from the tributaries, outflow at Fulton, channel degradation, and bank erosion were approximately in balance. Bank erosion sediment input to the numerical model was adjusted until the average annual outflow at Fulton, calculated using HEC-6W, for a 20-year hydrograph reasonably matched calculated annual outflow determined using a flow-duration curve and measured sediment data at Fulton.

2 Numerical Model

Model Description

The HEC-6W one-dimensional numerical sedimentation model was used to make predictions in this study. Mr. William A. Thomas initiated development of this computer program at the U.S. Army Engineer District, Little Rock, in 1967. Further development at the U.S. Army Engineer Hydrologic Engineering Center by Mr. Thomas produced the widely used HEC-6 Hydrologic Engineering Center (1993) generalized computer program for calculating scour and deposition in rivers and reservoirs. Additional modification and enhancement to the basic program by Mr. Thomas and his associates at the U.S. Army Engineer Research and Development Center (ERDC) led to the HEC-6W program currently in use. The program produces a one-dimensional model that simulates the response of the riverbed profile to sediment inflow, bed-material gradation, and hydraulic parameters. The model simulates a series of steady-state discharge events and their effects on the sediment transport capacity at cross sections and the resulting degradation or aggradation. The program calculates hydraulic parameters using a standard-step backwater method.

HEC-6W is a state-of-the-art program for use in mobile bed channels. The numerical model computations account for all the basic processes of sedimentation: erosion, entrainment, transportation, deposition, and compaction of the bed for the complete range of particle sizes found in the Red River. The model calculates aggradation and degradation of the streambed profile over the course of a hydrologic event. When applied by experts using good engineering judgment, the HEC-6W program will provide good insight into the behavior of mobile bed rivers such as the Red River.

Vicksburg District Model

A HEC-6 numerical model study had been conducted by Simons, Li and Associates (SLA) for the Vicksburg District (Simons, Li and Associates 1988). The model covered an approximately 175-mile reach of the Red River from Joe D. Waggonner Jr. Lock and Dam (Lock and Dam No. 5) at pre-Red River Waterway Project river mile 247.5 to Index, AR, at preproject river mile 425.3. The model geometry was based on the 1980-81 hydrographic survey. On the average, cross sections were located about 1.75 miles apart. Floodplain elevations for cross sections were determined using United States Geological Survey

(USGS) 7.5-min topographic maps and profiles of existing levees. The Bear, Mays Lake, Goose Lake, Brown Bend, Belcher, and Wilkerson Point realignments were included in the model. The downstream water-surface elevation was based on the operating pool schedule at Lock and Dam No. 5. Roughness coefficients were determined by matching stage-discharge measurements at the Shreveport (preproject river mile 277.2) and Fulton (preproject river mile 401.5) gages. It was found that channel hydraulic roughness coefficients varied with discharge, and were lower at higher discharges. Manning's roughness coefficients varied between 0.019 at 175,000 ft^3/sec, 0.024 at 15,000 ft^3/sec, and 0.030 at 4,000 ft^3/sec. Overbank roughness coefficients of 0.10 were assigned. Very-fine sand through fine gravel size classes were selected for use in the model. The Toffaleti (1968) transport equation was used to calculate sediment transport by size class. Bed material samples collected along the study reach were used to develop the initial representative bed-material gradations required for each cross section in the model. This initial gradation was adjusted until calculated sediment transport matched sediment transport measurements made at Fulton and Shreveport. Adjusted gradations were finer than measured gradations. Sediment inflow to the model was determined by assuming equilibrium sediment transport at the upstream boundary of the model and calculating sediment inflow. Sediment inflow from the tributaries was neglected.

The SLA HEC-6 numerical model was updated by the Vicksburg District in 1999 to include silts and clays. The Krone (1962) equation was used to calculate deposition of silts and clays. Ariathurai and Krone's (1976) modification of the Parthenaides (1965) equation was used to calculate erosion of silts and clays. The following cohesive sediment properties were assigned: shear stress threshold for deposition = 0.02 lbf/ft^2, shear stress threshold for particle erosion = 0.0163 lbf/ft^2, shear stress threshold for mass erosion = 0.1044 lbf/ft^2, mass erosion rate = 9.45 lbf/ft^2/hr, and the slope of the erosion rate curve was 110 /hr. Sediment inflow of silt and clay size classes were assigned as a constant percentage of the total sediment inflow. Clay was assigned to be 42 percent of the total sediment inflow and each silt size class was assigned to be 7 percent of the total sediment inflow. Thus, the silt and clay sediment sizes accounted for 70 percent of the total sediment inflow.

The Vicksburg District has determined that this numerical model adequately simulates existing aggradation and degradation trends in the Red River between Index and Lock and Dam No. 5. Therefore, the Vicksburg District numerical model was used as the base for this study downstream from Index. The geometry, adjusted bed-material gradation, and downstream water-surface rating curve from the Vicksburg District HEC-6 model were used in the numerical model for this study.

Geometry for Extended Model

The numerical model was extended from Index, AR, to Arthur City, TX, (river mile 633.1) using the 1969 degradation surveys provided by the Tulsa District. There is a discontinuity between Vicksburg District and Tulsa District stationing at Index. Index is located at Vicksburg District river mile 425.3, and Tulsa District river mile 485.3. In the numerical model a station equation occurs

at Index where the station river mile is increased by 60.0 miles. Floodplain elevations for the degradation ranges were determined using 7.5-min USGS quad maps. The degradation surveys between Index and Arthur City were located at distances between 11 and 24 miles, with an average of 15 miles. These distances between cross sections are far from ideal, making detailed evaluation of aggradation and degradation in specific reaches impossible. However, the model is adequate to estimate sediment transport past Fulton and the sediment delivered from the Index to Arthur City reach.

Roughness coefficients in the model were adjusted to match measured water-surface elevations at Index and Arthur City from specific gage curves (USAED, Tulsa, 1998). Roughness coefficients were higher for the extended model than for the downstream model due to unaccounted for expansion and contraction losses in the long reach lengths. The assigned channel roughness coefficients varied between 0.027 and 0.035 depending on the extent of meandering between cross sections. Overbank roughness coefficients of 0.15 were assigned. Calculated water-surface elevations for low discharges were below observed values at Arthur City. This is attributed to the poor channel definition due to the limited survey data between Index and Arthur City.

Hydrology

Denison Dam is located on the Red River at river mile 725.9. The dam was completed in 1944 and effectively captures the entire sediment load from a watershed of 39,720 square miles.

Downstream from Denison Dam runoff into the Red River is heavily influenced by reservoirs that have been constructed on the major tributaries. Three important tributaries enter the Red River between Denison Dam and Arthur City (river mile 633.1.) These are Sanders Creek, Blue River, and Muddy Boggy Creek. Pat Mayse Dam was constructed on Sanders Creek in 1966 and controls a drainage area of about 175 square miles. That leaves 4,636 square miles of uncontrolled watershed above the Arthur City gage. About 26 miles downstream from Arthur City is the confluence with the Kiamichi River. Hugo Reservoir was completed on the Kiamichi River in 1974 and controls 1,709 square miles of a 1,830-square mile drainage area. The DeKalb gage is located at river mile 556.9 and has an uncontrolled drainage area of 5,744 square miles. The Index gage is located at river mile 485.3 (Tulsa stationing) or 425.3 (Vicksburg stationing) and has an uncontrolled drainage area of 6,426 square miles. The Little River enters the Red River at preproject river mile 403 just upstream of the Fulton gage. Millwood Reservoir was completed on the Little River in 1966, controlling 4,144 square miles of a 4,239-square mile drainage area. Downstream from Fulton, the Sulphur River enters the Red River at preproject river mile 335 and is controlled by Wright Patman Reservoir, which was constructed in 1953. Cross Bayou enters the Red River at preproject river mile 278 and is controlled by Caddo Dam, which was originally completed in 1914 and reconstructed in 1971. The Sulphur River has a drainage area of 3,748 square miles and Cross Bayou has a drainage area of 3,517 square miles. Most of the sediment yield from the Red River watershed below Denison Dam is trapped behind these tributary reservoirs.

Sediment concentrations in the Red River are very small immediately downstream from Denison Dam (USAED, Tulsa, 1998). Between Denison Dam and the confluence of the Kiamichi River sediment is supplied from tributaries, bank erosion and bed degradation, and sediment concentrations increase in a downstream direction. The Arthur City gage reflects this increase in sediment concentration. In Figure 2, measured total sediment concentrations in the major tributaries between Denison Dam and Arthur City are compared to measured total sediment concentrations in the Red River. Sediment contributions from tributaries are essentially eliminated downstream from Arthur City. However, the total quantity of runoff is only slightly reduced by the reservoirs. The reservoirs then have the effect of decreasing the sediment concentration in the Red River downstream from Arthur City. The following tabulation summarizes the location of important features on the Red River and the relative size of the drainage areas.

	River Mile Tulsa stationing	River Mile Vicksburg stationing	Drainage Area square miles	Uncontrolled Drainage Area square miles	Year Dam Completed
Denison Dam	725.9		39,720	0	1944
Blue River	About 671		676	676	
Muddy Boggy Creek	About 644		2,429	2,429	
Sanders Creek	About 636		>175	?	1966
Arthur City gage	633.1		44,531	4,636	
Kiamichi River	About 606		1,830	121	1974
DeKalb gage	556.9		47,348	5,744	
Index gage	485.3	425.3	48,030	6,426	
Little River		403.1	4,239	95	1966
Fulton gage	463.0	401.5	52,336	6,588	
Sulphur River		334.8	3,748	305	1953
Cross Bayou		277.8	3,517	773	1971
Shreveport gage		277.2	60,613	7,905	

Mean daily discharge data were available for Arthur City for October 1936 to September 1999 from the USGS Web site. Mean daily discharges for DeKalb were available from the USGS Web site for October 1968 to September 1997. Mean daily discharges for Index were available from the USGS Web site for October 1936 to September 1999. Daily discharge measurements at Fulton and Shreveport between January 1979 and December 1999 were obtained from the Vicksburg District.

These data were used to develop flow-duration curves and a historical hydrograph for the 20-year period between October 1979 and September 1999. Flow-duration curves for Arthur City, Index, and Fulton are shown in Figure 3. These data were adjusted so mean daily discharges at downstream gages were always greater than the reported discharges at upstream gages after accounting for flood wave travel time. The flow-duration curves were used to calculate average annual sediment yield at Arthur City and Fulton.

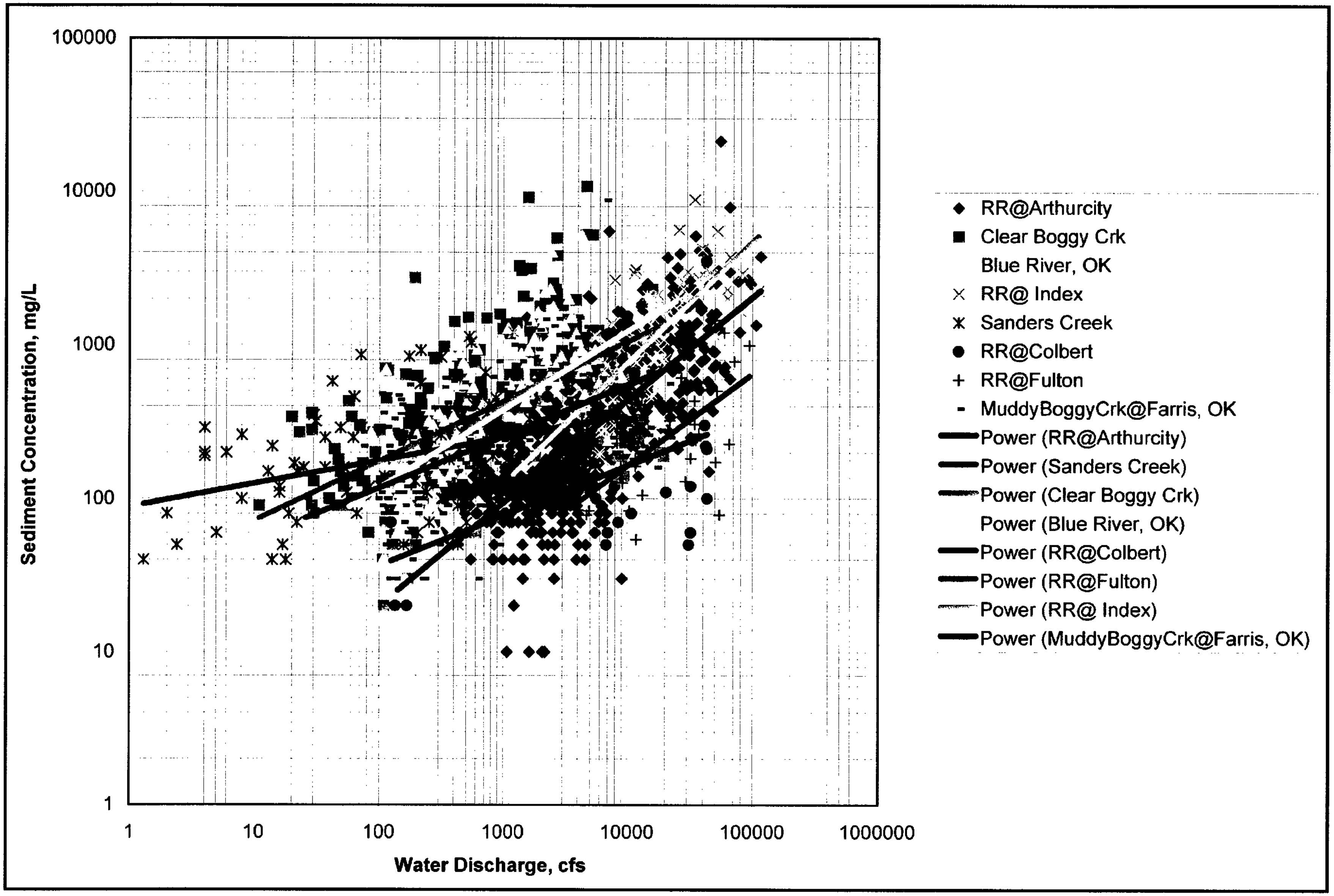

Figure 2. Total measured sediment concentrations (Blumer 1983) in Red River and tributaries

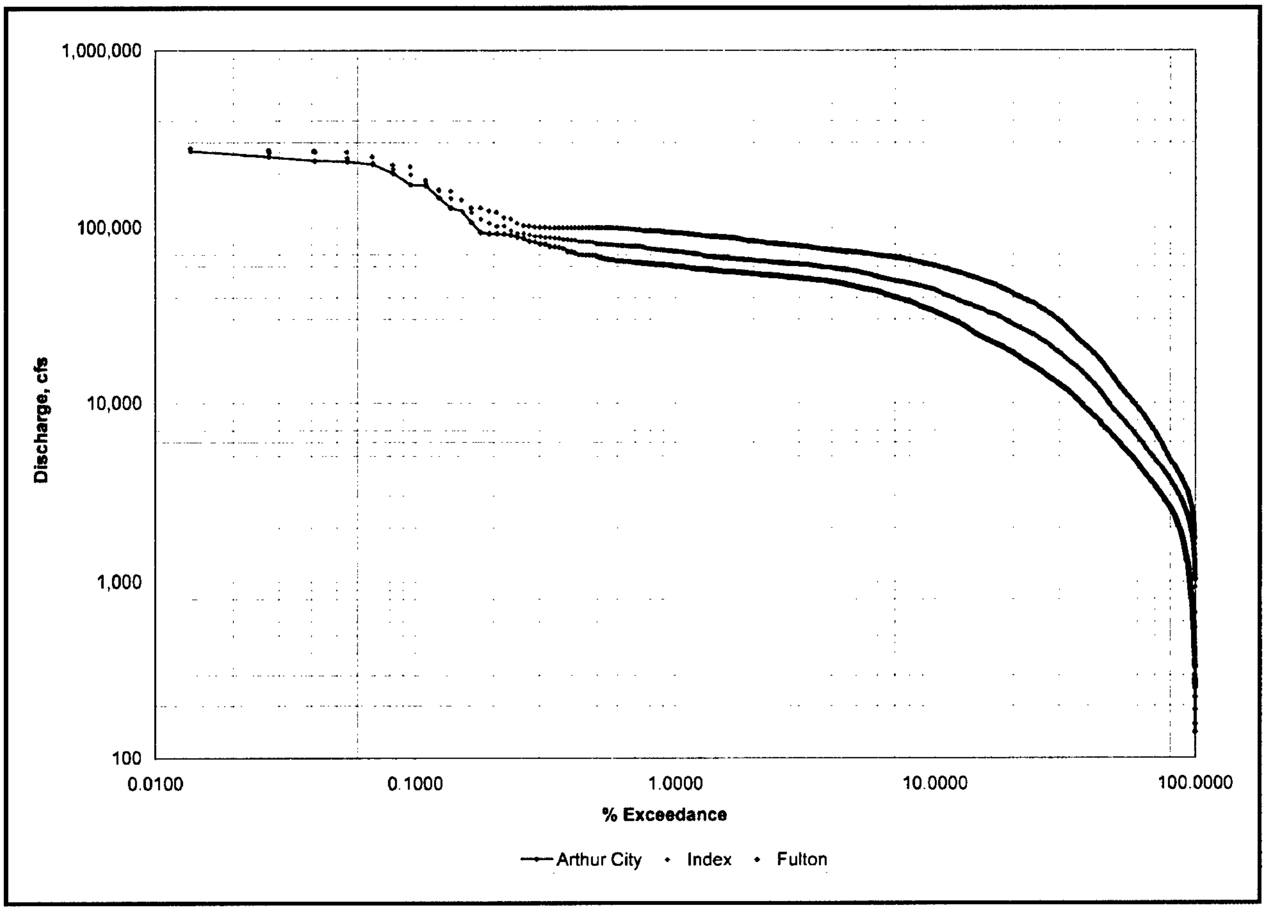

Figure 3. Red River flow-duration curves 1979-1999

A 20-year hydrograph was developed from the mean daily flow data. Approximate hydrograph lag times were determined from the reported data using regression analysis. Flow data at Fulton and Shreveport were plotted to estimate an appropriate lag time of two days. A 1-day lag was determined between Index and Fulton, and a 4-day lag between Arthur City and Index. The reported data were adjusted so flows from downstream gages were always greater than the flows upstream. The combined tributary inflow from the Sulphur River and Cross Bayou was estimated as the flow difference between the Shreveport and Fulton gages. The flow distribution from the Sulphur River and Cross Bayou were determined as a ratio of their drainage areas, which was the procedure used in the Simons, Li and Associates (1988) study. The Little River inflow was taken as the difference in the Index and Fulton gages. The inflow from the Kiamichi River was taken to be the difference in the Arthur City and Index gages.

Bed Material Gradations

The adjusted bed material gradations between Shreveport and Index used in the 1988 Simons, Li and Associates study were retained in the new model. During the course of the Simons, Li and Associates study, these bed gradations

had been adjusted from field measurements to better replicate measured suspended sediment data at Shreveport (Simons, Li and Associates, 1988).

In the extended numerical model, bed material gradations between Index and Arthur City were interpolated between the Simons, Li and Associates gradation at Index and an average value determined from field measurements collected in the vicinity of Arthur City (Derrick et al. 2000). Bed material gradations used in the numerical model are shown in Figure 4.

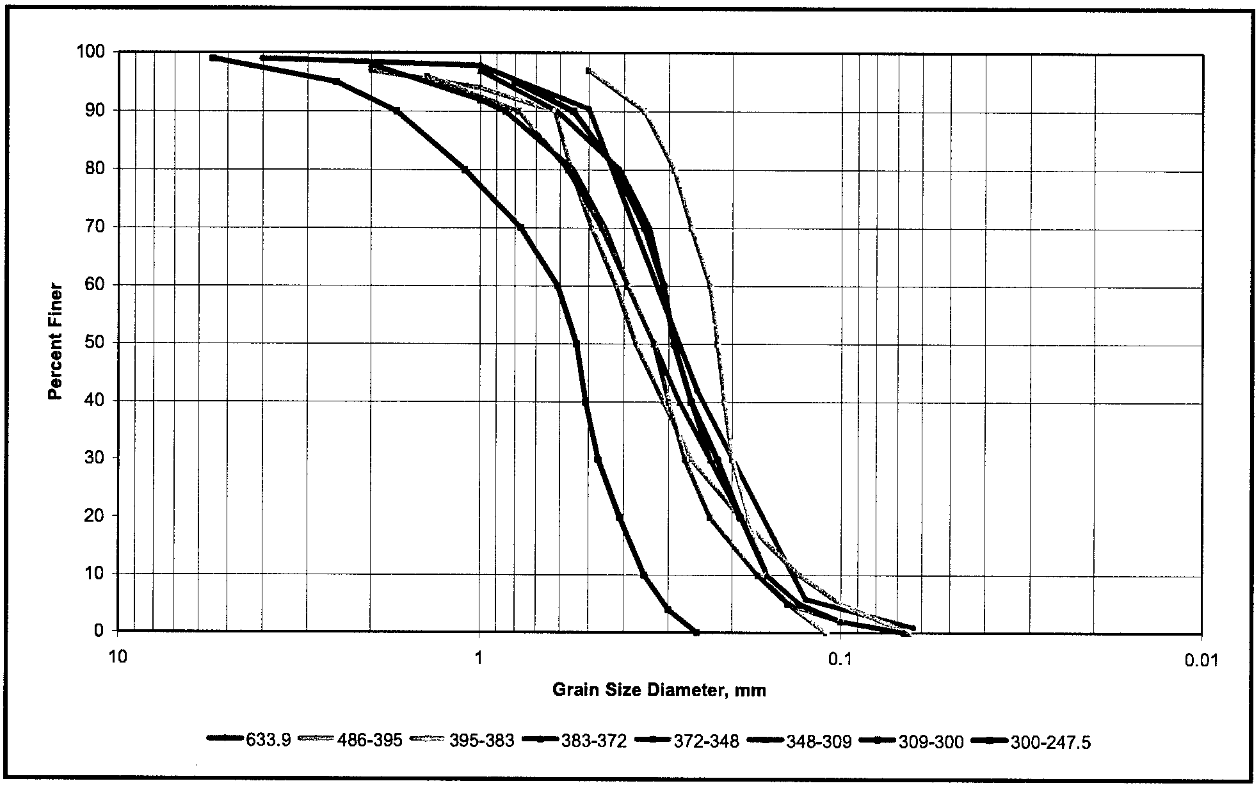

Figure 4. Bed material gradations used in numerical model between specified river miles

Sediment Transport Equation

Sediment sizes modeled in the numerical model varied between clay and coarse sand. Sediment transport of clay, very fine silt, and fine silt were calculated using Ariathurai and Krone's (1976) modification of the Parthenaides (1965) equation when erosion was occurring. Sediment transport of these sizes was calculated using Krone's (1962) equation when deposition was occurring. Cohesive sediment parameters were retained from the Vicksburg District numerical model.

One objective of this study was to better simulate sediment transport of the coarse and medium silt sizes. To accomplish this objective, a sediment transport equation applicable to both sand and coarse silt transport was used in lieu of the Toffaleti equation that had been used in the Vicksburg District model. The Laursen (1958) sediment transport equation modified by Madden (1963) was used to calculate sediment transport of medium and coarse silt and sand for this

study. This equation was chosen because it is the only equation developed using both sand and silt size classes. The HEC-6W code was modified for this study to allow coarse silt and medium silt to be transported using the Laursen-Madden sediment transport equation.

Sediment Inflow

Upstream boundary

Sediment inflow at the upstream boundary of the numerical model was determined from suspended sediment measurements taken at Arthur City, TX (river mile 633.1). Total measured suspended sediment data were available between 1938-1978 (Blumer 1983). In this study the most recent 20 years of record (1958–1977) were used. Between 1965 and 1977 size class analysis data were available at Arthur City (U.S. Army Engineer Division, Southwest (undated, a,b)) (see Table A1).

Using 744 sediment concentration measurements taken at Arthur City between 1958 and 1977, and a flow-duration curve developed from 1979-1999 mean-daily flow data at Arthur City, an average annual sediment load of 13.96 × 10^6 tons was calculated. The unbiased sediment regression curve used in this calculation is shown in Figure 5. Unbiased rating curves account for the error introduced when the least-squares regression approach is applied to the logarithmic values plotted in the regression analysis. Figure 5 also shows the

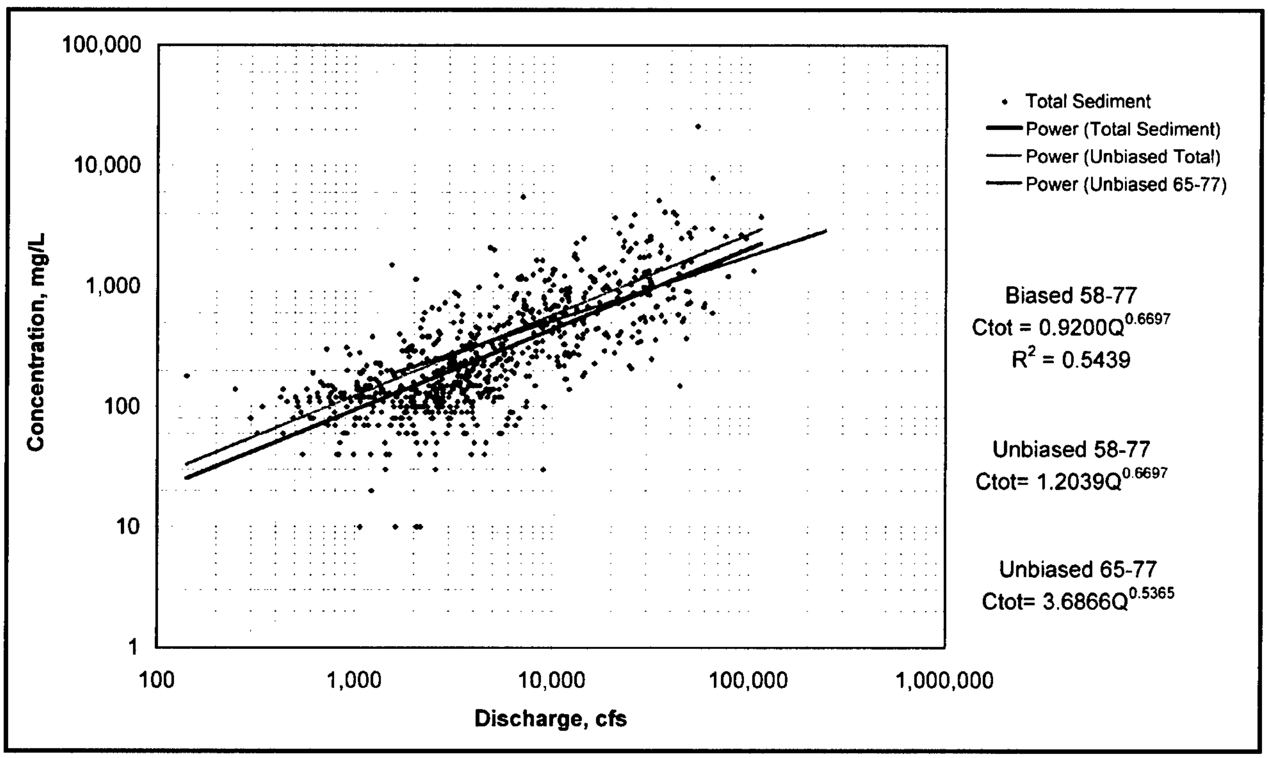

Figure 5. Total measured sediment concentration at Arthur City, TX, 1958-77 and 1965-77

unbiased regression curve developed from 109 measurements taken at Arthur City between 1965 and 1977. The 1965-77 data included particle size distributions and were used to determine size class fractions for the sediment inflow. Note that the 1965-77 data indicate a slightly lower sediment load at higher discharges than the 1958-77 data. This difference is considered insignificant given the scatter of data. In fact, when regression curves were developed for 5-year increments of sediment data (Figure 6), it was apparent that there was no trend in sediment transport at Arthur City. The 1965-77 data were used to determine the measured sand fraction of the total measured load. This was found to be 0.252. The measured sand load was increased by 10 percent to account for unmeasured sand load, resulting in a revised measured annual load past Arthur City of 14.32×10^6 tons/year.

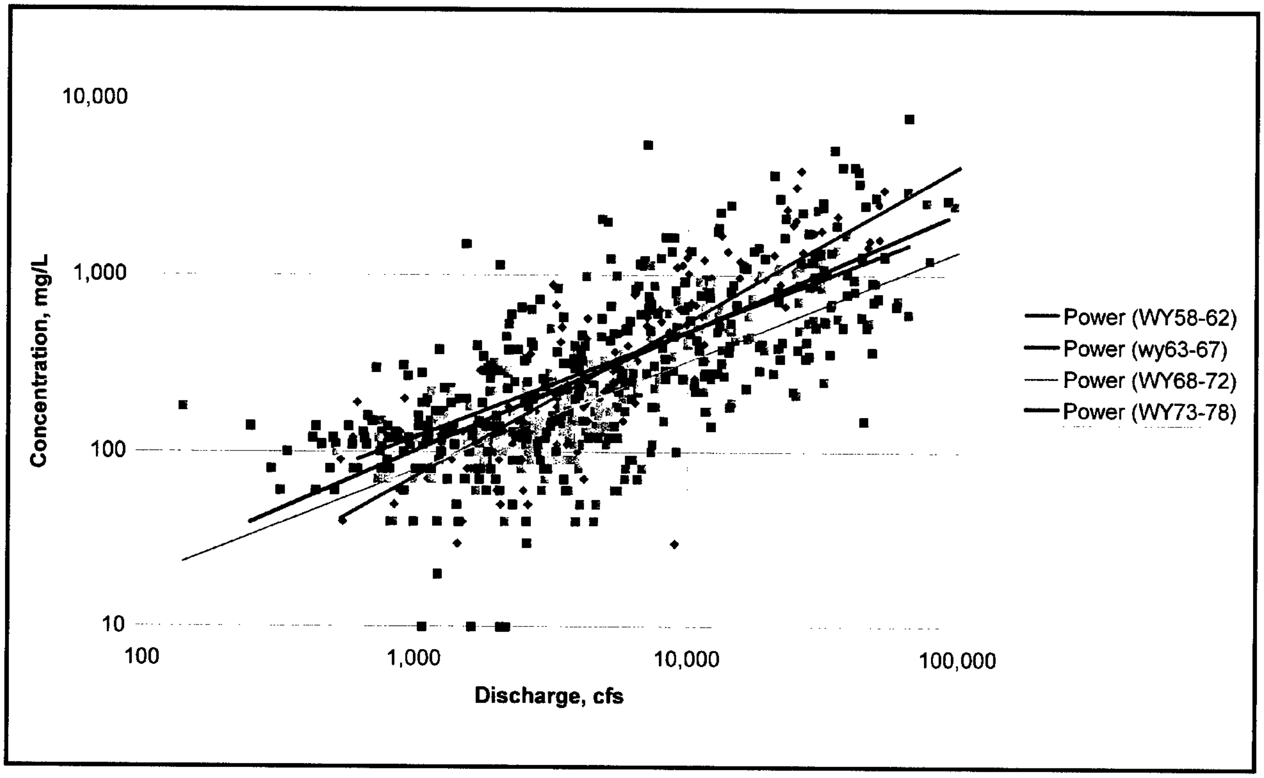

Figure 6. Five-year incremental sediment transport regression curves for Arthur City, TX

Unbiased regression curves developed from 109 measurements taken at Arthur City between 1965 and 1977 were used to determine size class fractions for the sediment inflow. These regression curves are shown in Plates 1-8. The total sediment load was determined from the unbiased regression curve developed from the 1958-77 total measured suspended sediment data. The rating curve for coarse sand was determined from Fulton data because there were no data for coarse sand available at Arthur City. The sediment-inflow rating curve for the HEC-6W numerical model at Arthur City is shown in the following tabulation:

Discharge ft^3/s	100	1,000	5,000	10,000	50,000	100,000	300,000
	tons/day						
Clay	1.8	60	1,030	3,401	50,546	156,690	909,096
Very fine silt	1.6	54	598	1,630	15,533	39,770	170,409
Fine silt	1.2	40	446	1,222	11,811	30,419	131,563
Medium silt	2.3	77	788	2,082	18,479	45,880	187,227
Coarse silt	1.3	43	728	2,396	35,389	109,423	632,282
Very fine sand	0.8	29	770	3,059	69,838	260,472	2,025,937
Fine sand	0.7	24	495	1,753	30,674	102,019	661,726
Medium sand	0.3	11	151	450	5,291	14,823	73,250
Coarse sand	0.1	2	24	59	590	1,730	8,470

Using the preceding sediment inflow rating curves, the total sediment inflow at Arthur City is 14.32×10^6 tons/year of which 6.10×10^6 tons/year is sand.

Tributaries

Tributaries below Arthur City are all controlled by reservoirs. Therefore sediment inflow from tributaries was neglected in this study. This is consistent with assumptions made by Simons, Li and Associates (1988).

Bank erosion

The difference between the total sediment load at Fulton and Arthur City is supplied by a) bank erosion, b) tributary inflow, and/or c) degradation. It was assumed in this study that the upstream reservoirs would effectively eliminate the sediment contribution from tributaries between Arthur City and Fulton. Therefore, the combined mean annual sediment inflow from bank erosion and degradation was determined to be the difference in the calculated mean annual sediment loads at Arthur City and Fulton.

Suspended sediment measurements were made at Fulton in 1975, 1978-79 (Blumer 1983), and between 1984 and 1996. Regression curves were developed for the 1975, 1978-79 data and compared to the more recent data (Figure 7). These curves show no apparent trend in sediment transport at Fulton. Between 1984 and 1996 sediment measurements were made at four verticals using standardized isokinetic sediment samplers. The 1984-96 data were used in this study to develop unbiased sediment rating curves for the total sediment load and for the sand load (Figure 8, Table A2). Unbiased rating curves account for the error introduced when the least-squares regression approach is applied to the logarithmic values plotted in the regression analysis. These unbiased sediment-rating curves and the flow-duration curve at Fulton developed from 1979-1999 historical mean daily discharges were used to determine the mean annual sediment loads at Fulton. The sand load was increased by 10 percent to account for the unmeasured load. Calculated total sediment yield at Fulton was 16.13 million tons/year and sand yield was 8.80 million tons/year. This calculated yield is less

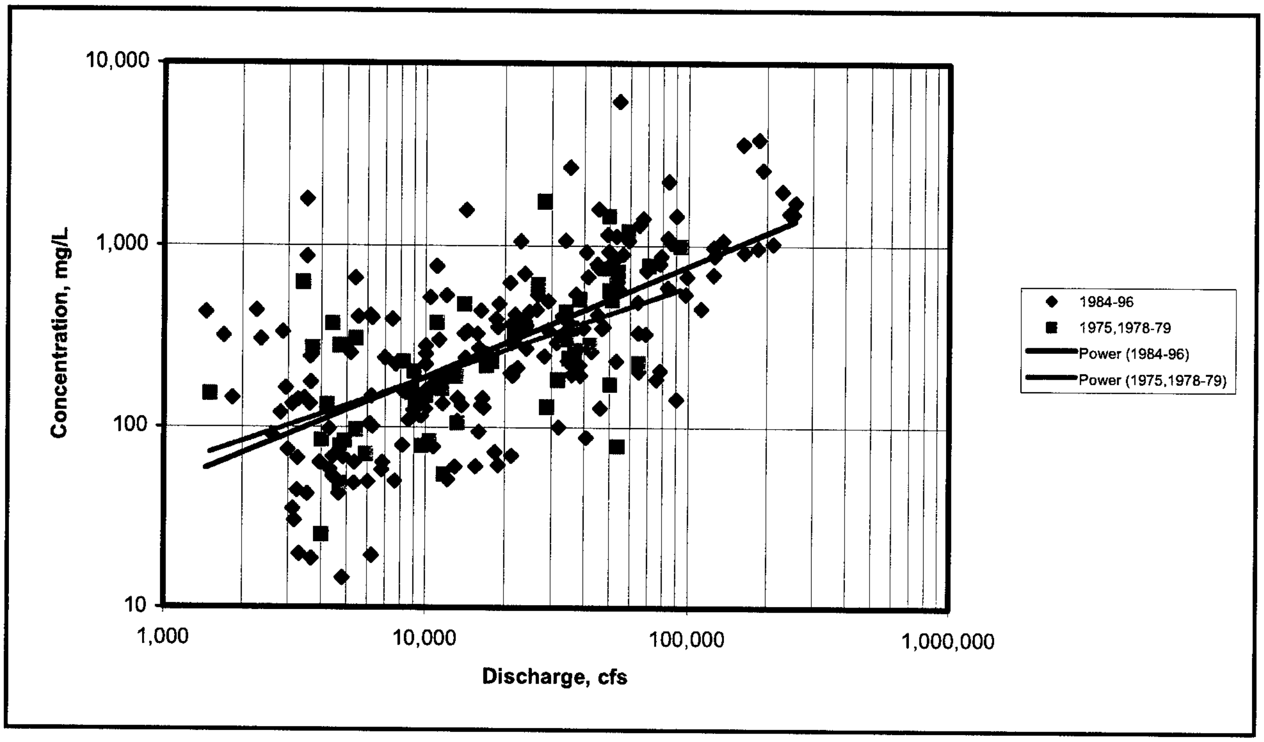

Figure 7. Comparison of historical sediment measurements, Red River at Fulton, AR

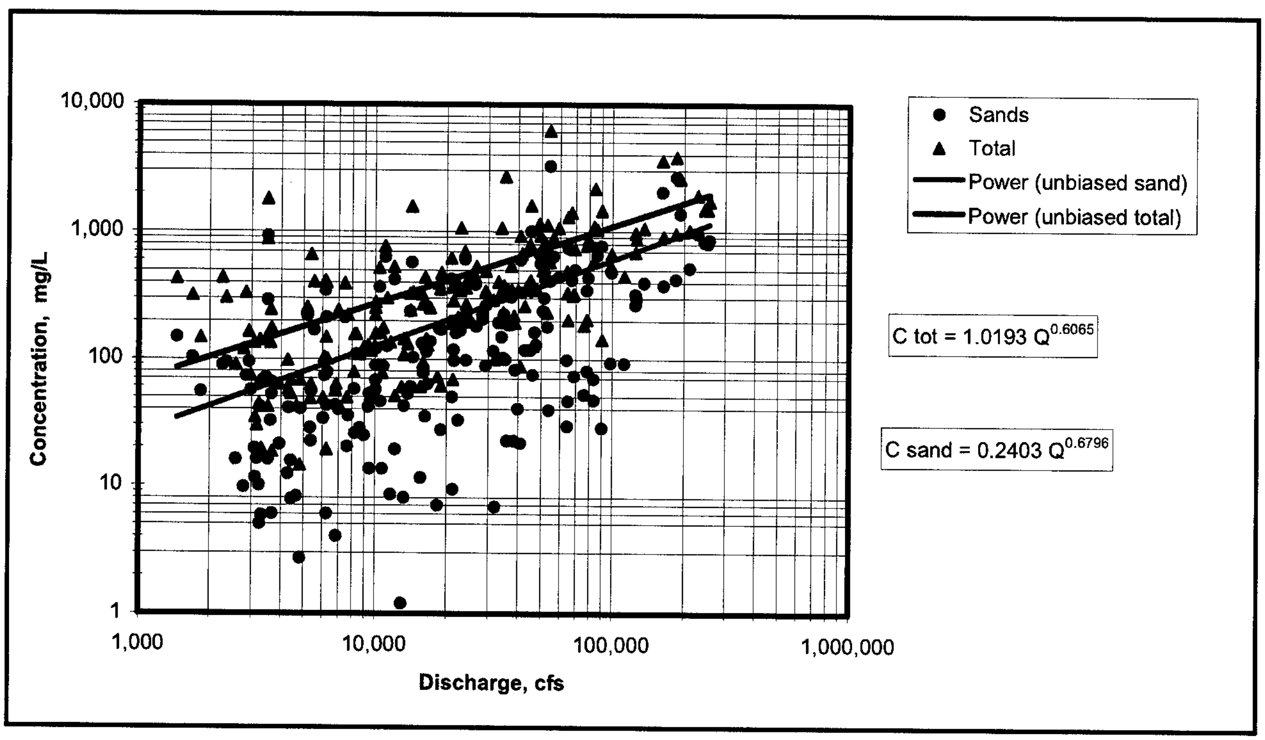

Figure 8. Unbiased predictors for measured total and sand loads at Fulton, AR, from 1984–96

than the 25 million tons/year annual suspended sediment load reported by USAED, New Orleans (1966) for Index.

The calculated total sediment inflow at Arthur City was 14.32 x 10^6 tons/year and sand inflow was 6.10 × 10^6 tons/year. The calculated difference in total annual sediment load between Arthur City and Fulton was 1.81 × 10^6 tons/year. Initially, during the model circumstantiation phase of the study, the total difference in sediment yield was assigned to bank erosion (1.81 × 10^6 tons/year.) With this assignment, the HEC-6W model calculated degradation between Arthur City and Fulton of about 0.92 × 10^6 tons/year and sediment transport past Fulton of about 17.2 × 10^6 tons/year. The calculated sediment transport past Fulton was about 7 percent too high when compared to the measured sediment transport of 16.13 × 10^6 tons/year. Next, bank erosion of 1.40 × 10^6 tons/year was assigned. With this assignment the HEC-6W model calculated degradation between Arthur City and Fulton of about 1.03 × 10^6 tons/year and sediment transport past Fulton of about 16.75 × 10^6 tons/year. Calculated sediment transport past Fulton was within 4 percent of measured sediment transport. The assigned bank erosion rate of 1.40 × 10^6 tons/year was deemed appropriate for purposes of this study.

The following tabulation summarizes the comparison between measured and calculated sediment transport with the HEC-6W numerical model. The prescribed sediment inflow at Arthur City is 14.32 × 10^6 tons/year of which 6.10 × 10^6 tons/year is sand. Assigned sediment inflow from bank erosion is 1.40 × 10^6 tons/year of which 0.67 × 10^6 tons/year is sand. Calculated degradation is 1.03 × 10^6 tons/year. Calculated sediment transport at Fulton is 16.75 × 10^6 tons/year of which 7.84 × 10^6 tons/year is sand. This compares to measured sediment transport at Fulton of 16.13 × 10^6 tons/year, of which 8.8 × 10^6 tons/year is sand (with 10 percent added for unmeasured sand load.)

Comparison of Measured and Calculated Sediment Loads

	Measured million tons/year	Measured with 10% added for unmeasured sand million tons/year	Assigned million tons/year	Calculated million tons/year
Arthur City	13.96	14.32	14.32	
Fulton	15.33	16.13		16.75 (17.88)
Bank erosion			1.40 (2.8)	
Degradation				1.03 (0.76)

There are inherent errors associated with both the measured data and the numerical model boundary assignments. When sand yields from the measured data are compared, the annual yield at Fulton is 2.70 × 10^6 tons/year greater than Arthur City. However, the total yield is only 1.81 × 10^6 tons/year greater. This means that there is an error in the measurements, or that considerable quantities of silt and clay are depositing between the two gages while sand transport is increasing, which is highly unlikely. Comparing measured sediment concentrations provided a combined contribution from bank erosion and degradation of

1.81×10^6 tons/ year. The numerical model calculated a combined 2.43×10^6 tons/year from bank erosion and degradation. Thus, the numerical model calculated a total load past Fulton that is still too high. One might conclude that the bank erosion rate should be reduced more. However, looking at just the sand load, we see that the measured load at Fulton is 8.80×10^6 tons/year, but the numerical model calculates only 7.84×10^6 tons/year. Further reduction in the bank erosion would increase this error. A bank erosion rate of 1.40×10^6 tons/year was settled on for this study to represent the most probable condition. But a higher rate of 2.80×10^6 tons/year was also evaluated to determine the sensitivity of deposition quantities to a higher bank erosion rate assignment.

Bank material gradations

Derrick et al. (2000) collected sediment samples in July 2000 from the banks of Red River between river miles 629 and 639. This reach is in the vicinity of the Highway 271 Bridge at Arthur City. Fifteen samples were collected with a scoop and bagged. Sediment gradations were determined using a Coulter LS Particle Size Analyzer, a near-forward laser diffraction measurement device. An average bank gradation was determined from these samples and the banks were found to consist of both silt and sand in about equal proportions. Maximum and minimum bank gradations are plotted with the average bank gradation in Figure 9. Data are provided in Table A3, Appendix A.

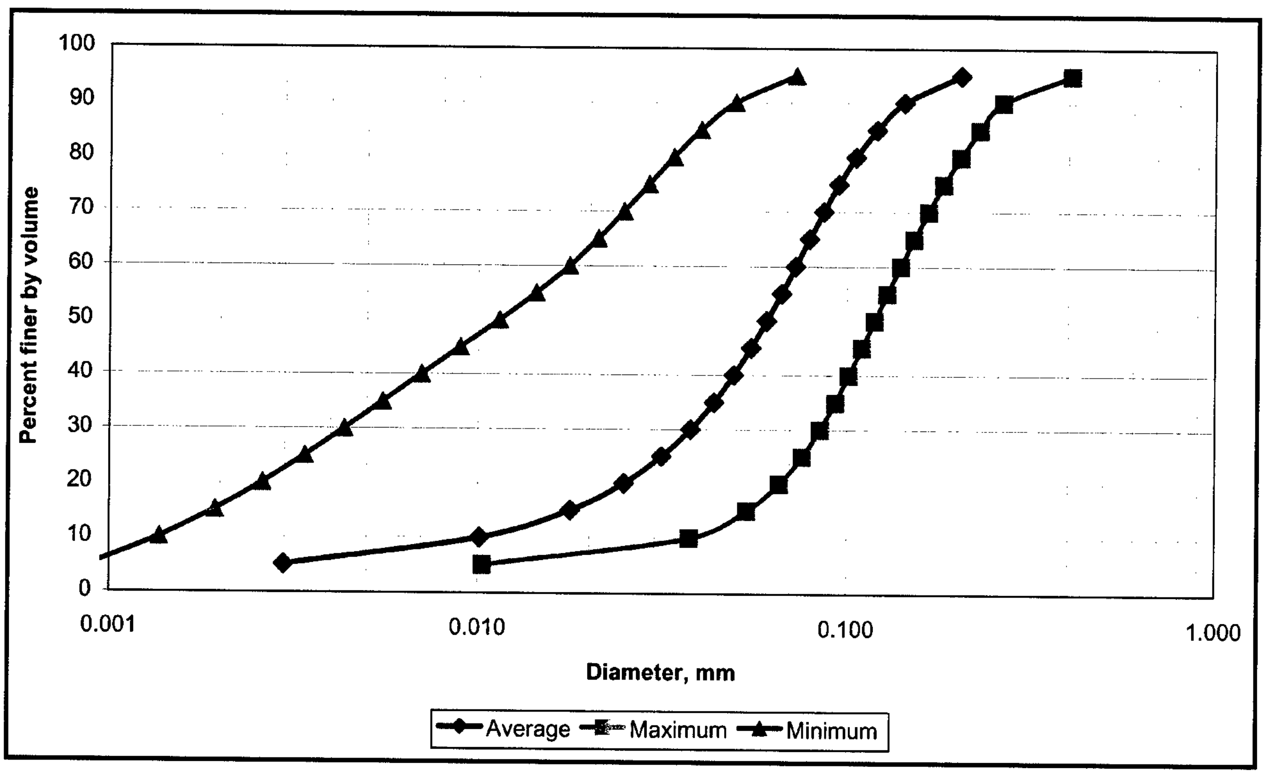

Figure 9. Red River bank gradation vicinity of Arthur City, TX

Using the average bank gradation curve the following percentages were determined for each sediment size class. These percentages were assumed to be representative of the entire reach between Arthur City and Index and were used to determine the gradation of sediment inflow from bank erosion in the numerical model.

Bank Material Size Fractions	
Size Class	Percentage
Clay	6
Very Fine Silt	2
Fine Silt	6
Medium Silt	12
Coarse Silt	26
Very Fine Sand	34
Fine Sand	10
Medium Sand	4

Distribution of sediment inflow from bank erosion

The surface area extent of both bank erosion and deposition in the Red River between Denison Dam and Index had been determined in a previous study (USAED, Tulsa, 1998). A combination of image interpretation and Geographic Information System (GIS) techniques were used in that study. High-resolution satellite imagery was selected at two points in time, 1987 and 1996. The bank line was interpreted and delineated on each set of imagery. The two images were then overlaid to identify locations where the bank line had changed. Zones of erosion and deposition were delineated and the surface area calculated. Surface area changes were determined for 5-mile increments of the river. These data were used in this study to determine the percentage of total bank erosion between Arthur City and Index that would be assigned at each cross section in the reach. In the numerical model a constant sediment inflow rate was used throughout the simulation. The results are shown in the following tabulation.

Distribution of Sediment Inflow From Bank Erosion Between Arthur City, TX, and Index, AR				
Cross section River mile	Erosion acres	Deposition acres	Percentage based on surface area differences	Daily average for a total of 1.40×10^6 tons/year tons/day
620.9	1,253	239	31	1,234
606.9	580	174	12	472
595.3	1,045	937	3	118
571.6	1,306	812	15	589
558.7	518	232	9	354
546.8	344	230	4	157
532.1	638	576	2	79
514.5	459	214	8	315
495.9	421	165	8	315
462.3	452	180	8	315

A sensitivity analysis was conducted to determine if allowing bank erosion to occur only at high discharges would significantly affect calculated results. In the sensitivity analysis bank erosion of 1.40×10^6 tons/year was maintained, but bank erosion was allowed only when the discharge at Index exceeded 50,000 cfs. Calculated deposition between Lock and Dam No. 5 and I-220 was increased by only 0.3 percent during a 20-year simulation with this modification. The variation of bank erosion with discharge was deemed insignificant for determining long-term deposition patterns in the lower reaches of the numerical model.

3 Model Circumstantiation

Specific Gage Comparisons

Model predictive performance was compared to specific gage degradation rates at Index, AR, and Arthur City, TX. Specific gage degradation rates were obtained from the 1998 sediment transport study (USAED, Tulsa, 1998.) The model predicted specific gage degradation rates that were greater than observed rates. At Index specific gage degradation rates were 30 to 100 percent greater than observed rates. At Arthur City calculated specific gage degradation rates were three to six times greater than observed rates. The larger difference at Arthur City is attributed to the sparse number of cross sections between these two gages. Doubling sediment inflow at the upstream boundary and doubling the bank erosion rates had an insignificant effect on specific gage degradation rates. The existing model should not be used to provide quantitative estimates of specific gage degradation.

Sediment Transport at Fulton, AR

Model performance was evaluated by comparing calculated and measured sediment transport volume at Fulton, AR. The model calculated a sediment transport volume within 4 percent of the measured volume adjusted to account for unmeasured load. The estimated total annual sediment load past Fulton based on sediment measurements was 16.13 million tons and the calculated total sediment load past Fulton was 16.75 million tons. The calculated annual sediment budget for this reach of the Red River is 14.32 million tons inflow past Arthur City, 1.40 million tons inflow from bank erosion, 1.03 million tons inflow from degradation and 16.75 million tons outflow past Fulton. The existing model is adequate to evaluate the effect of reducing bank erosion on sediment transport past Fulton and deposition in the navigation channel downstream.

Calculated and measured sediment transport rates by size class were compared at Fulton. Size class data for sand sizes were available at Fulton for 1984–1996 (Figure 10). Calculated sediment transport for each sand size class for randomly selected days in the numerical simulation are compared to the measured data in Figures 11 to 16.

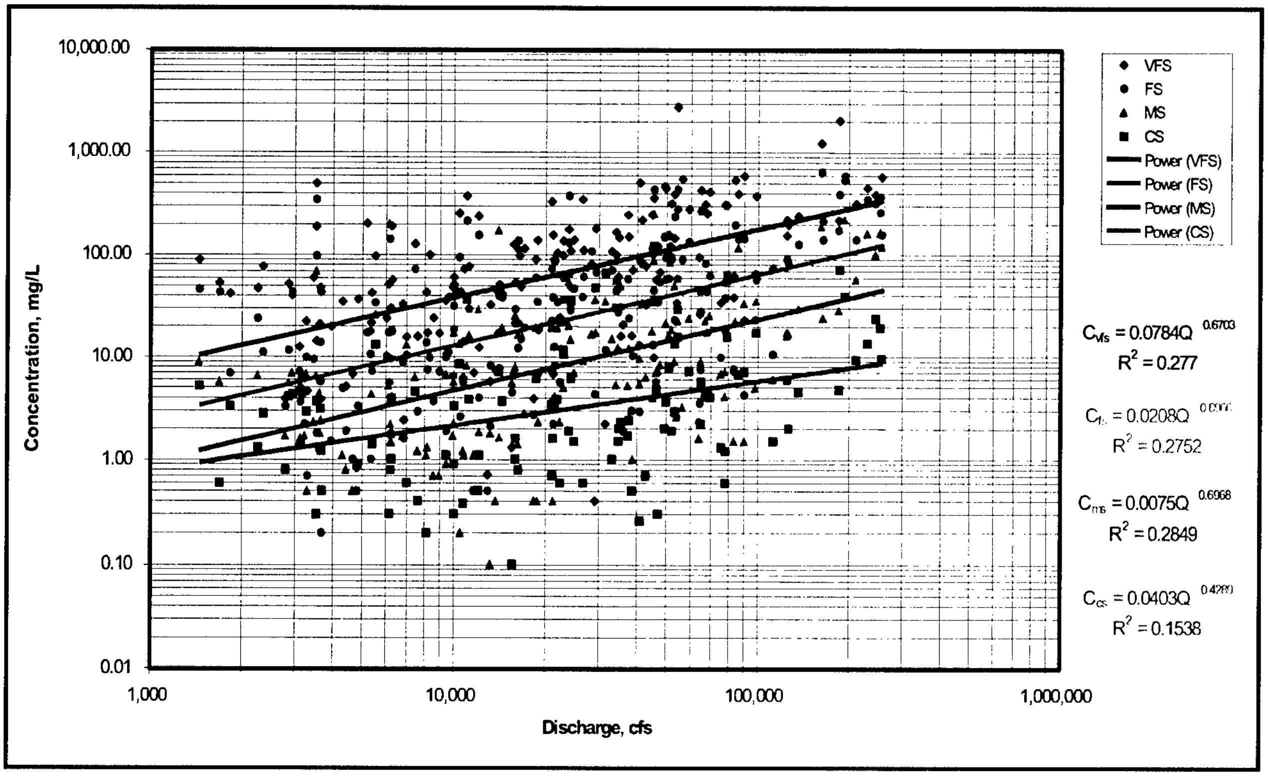

Figure 10. 1988-96 suspended sand measurements at Fulton, AR

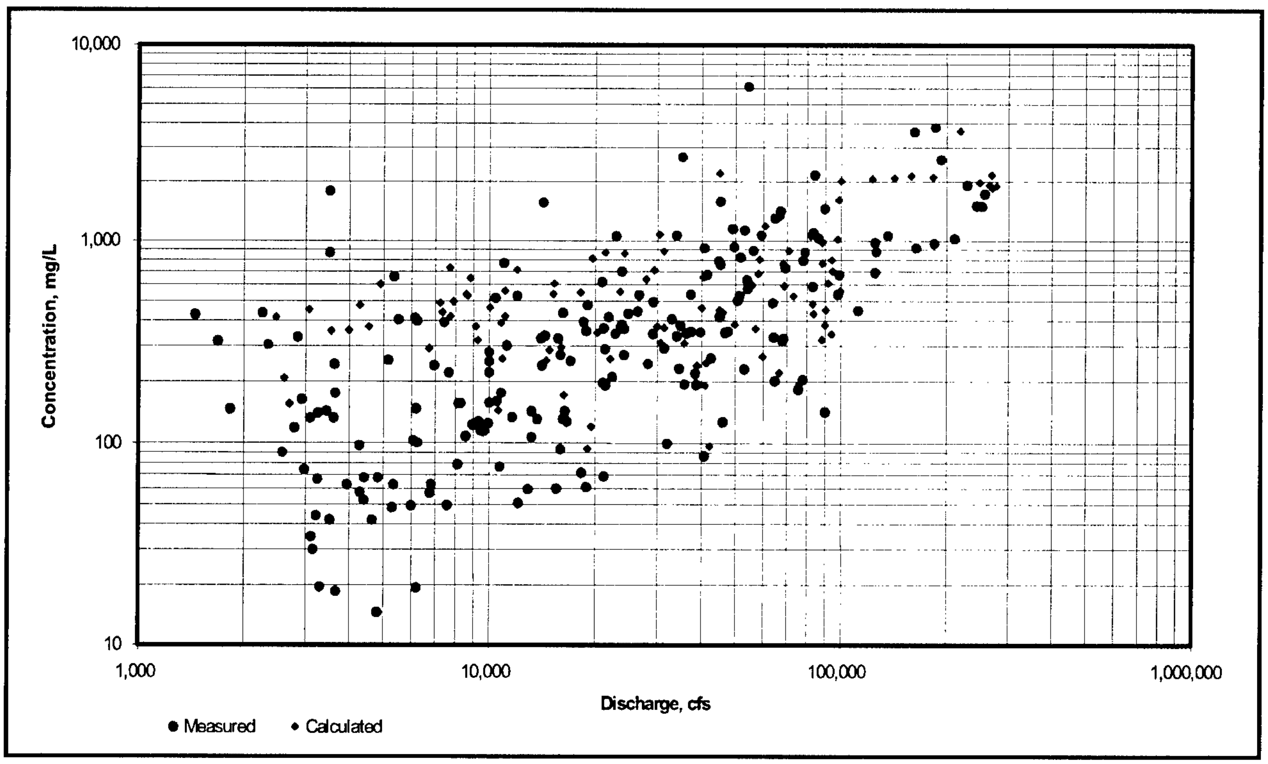

Figure 11. Comparison of measured and calculated total sediment transport at Fulton, AR, 1984-1996

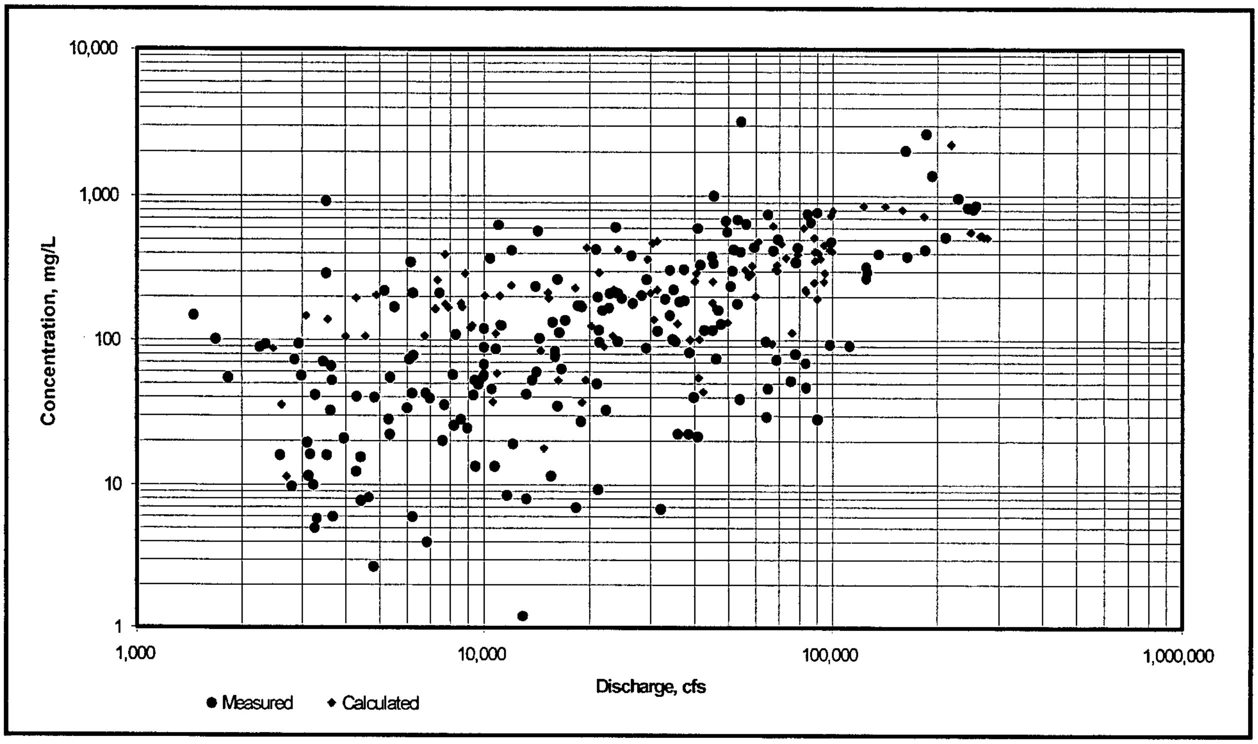

Figure 12. Comparison of measured and calculated total sand transport at Fulton, AR, 1984-1996

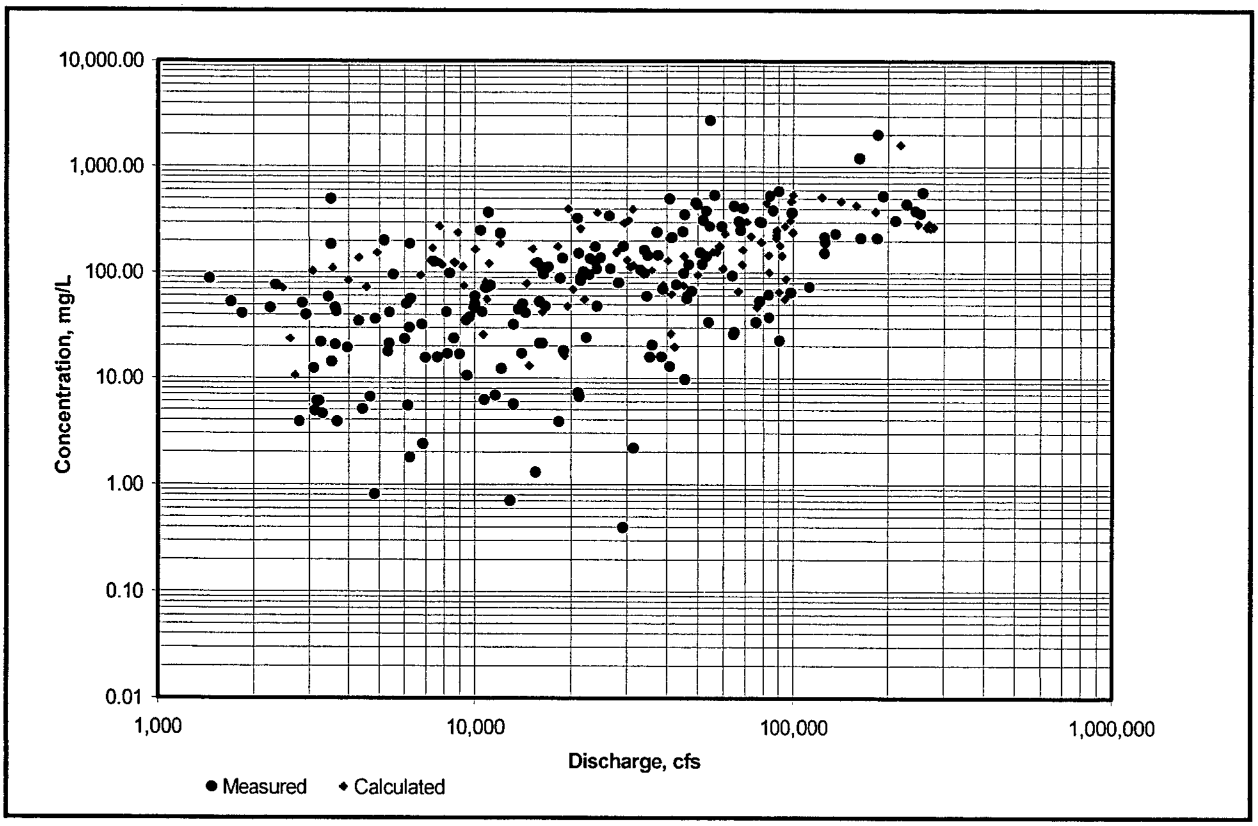

Figure 13. Comparison of measured and calculated very-fine sand transport at Fulton, AR, 1984-1996

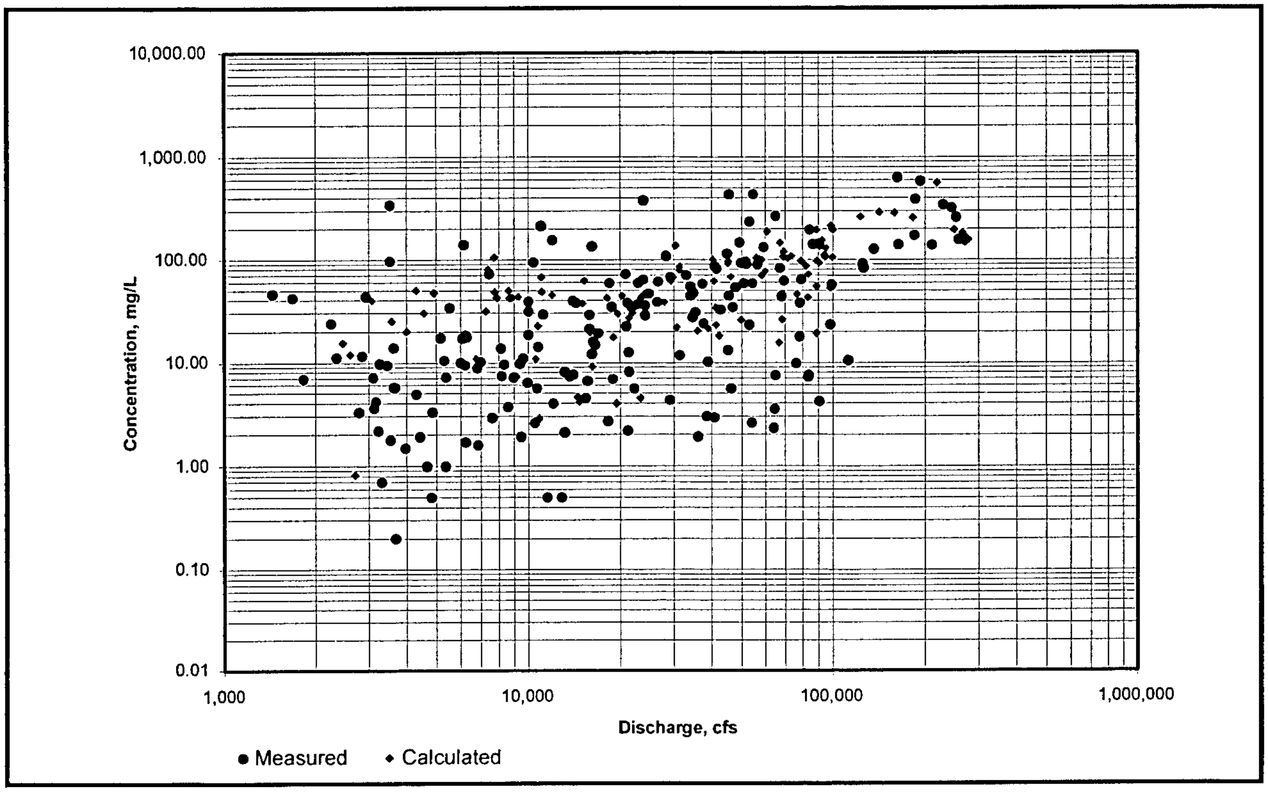

Figure 14. Comparison of measured and calculated fine sand transport at Fulton, AR, 1984-1996

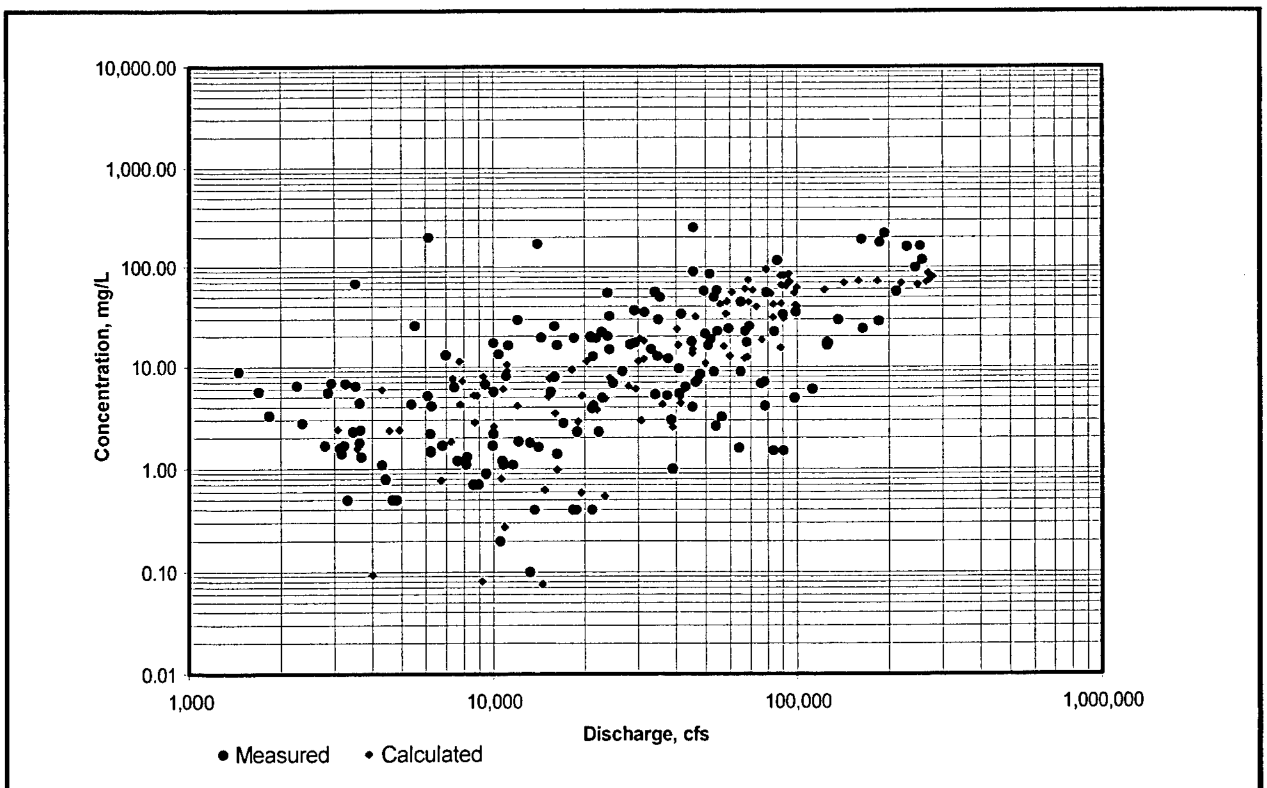

Figure 15. Comparison of measured and calculated medium sand transport at Fulton, AR, 1984-1996

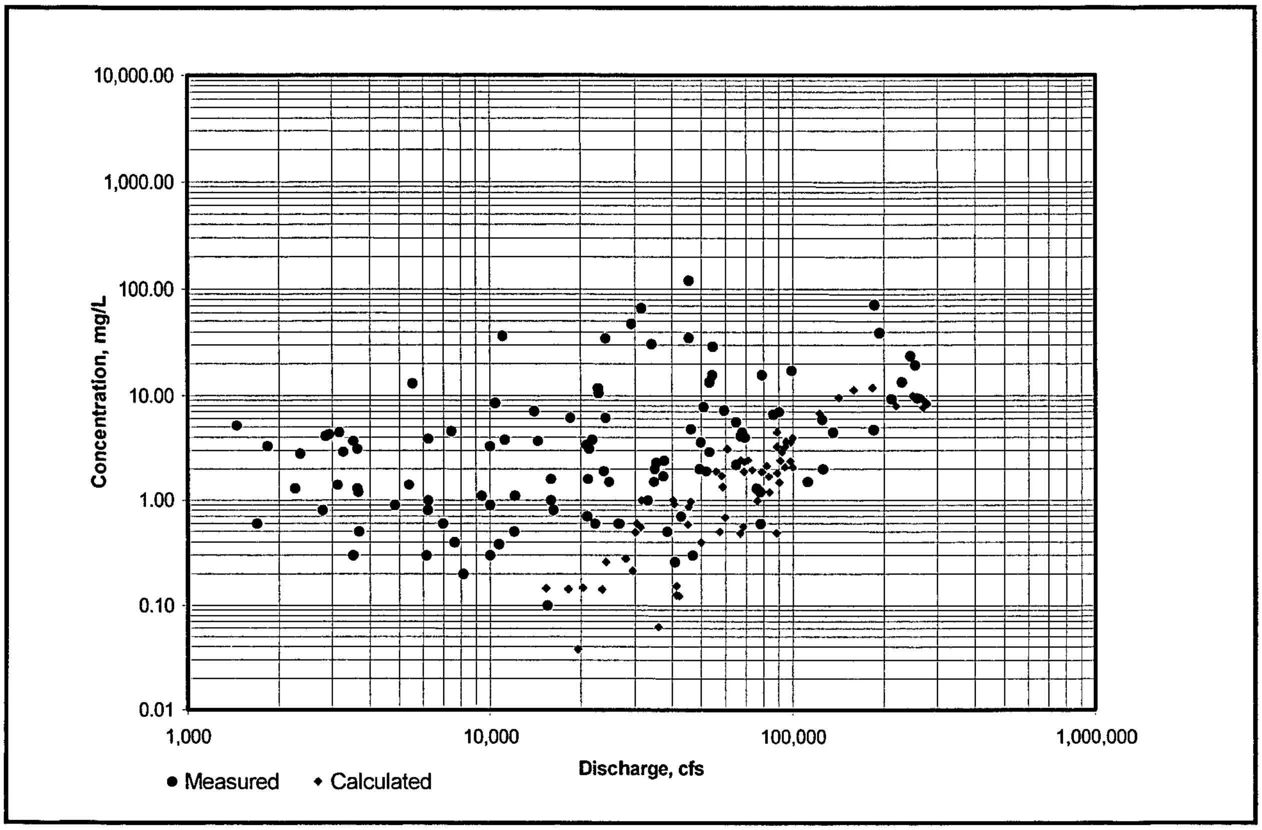

Figure 16. Comparison of measured and calculated coarse sand transport at Fulton, AR, 1984-1996

Calculated sediment transport at Fulton closely duplicates measured sediment transport rates for all sediment size classes except coarse sand. Calculated coarse sand transport is considerably lower at discharges less than 100,000 cfs. Coarse sand, however, constitutes only a small fraction of the total sediment load. The wide range in both measured and calculated sediment concentration is due to the variability of inflow from the Little River, which has negligible sediment concentration. These comparisons provide confidence that the numerical model is adequately simulating sediment transport by size class.

Uncertainties

The numerical model adequately simulates sediment transport, but the model's predictive capabilities are limited by several uncertainties. There are uncertainties related to the sediment measurements, tributary sediment inflow, volume of bank erosion and the gradation of the eroded bank material.

Sediment measurements used to determine sediment inflow at Arthur City were taken between 1958 and 1977. These years do not correspond to the historical hydrograph used in the numerical model (1979-1999) nor to the measurements at Fulton, which were taken between 1984 and 1996. It was assumed that since there have been no reservoirs constructed in the watershed above Arthur City that the sediment yield has not changed since 1958. Measured sediment

loads exclude the sediment load that moves beneath the sediment sampler. This includes the entire bed load. In this study, sand load was increased 10 percent to account for this unmeasured load.

It was assumed in this study that sediment inflow from tributaries was negligible. However, it is unlikely that no sediment inflow occurs from these tributaries.

Annual bank erosion rates were assigned in the numerical model so that the combined contribution of sediment from the banks and the riverbed provided a reasonable quantity of sediment at Fulton. However, due to the poor channel definition from so few cross sections, the calculated degradation rate may be too high and the bank erosion rate too low. In addition, the percentages of each size class from eroded banks are based on a few measurements of bank material in the vicinity of Arthur City.

These uncertainties must be considered when model results are evaluated.

4 Study Results

Upstream from Lock and Dam No. 5

Upstream from the Joe D. Waggonner Jr. Lock and Dam (preproject river mile 247.5), the J. Bennett Johnston Waterway is currently maintained up to the Caddo-Bossier Port (preproject river mile 260). The authorized upstream terminus of the waterway is the Interstate-220 bridge at preproject river mile 283.5. However, no maintenance is conducted upstream from the port. The HEC-6W numerical model was used to calculate average annual sediment deposition in the waterway. Results are shown in Table 1.

Table 1
Calculated Deposition Upstream from Joe D. Waggonner Jr. Lock and Dam, million tons/year

	Between Lock and Dam and Port RM 247.5 – 260.9		Between Port and I-220 RM 260.9 - 283.0		Total Between Lock and Dam and I-220 RM 247.5 – 283.0	
	Deposition	Difference from existing	Deposition	Difference from existing	Deposition	Difference from existing
Existing bank erosion	3.648		1.306		4.954	
50 percent of existing bank erosion	3.628	- 0.020	1.291	- 0.015	4.919	- 0.035
0 percent of existing bank erosion	3.599	- 0.049	1.273	- 0.033	4.872	- 0.082
200 percent of existing bank erosion	3.702	+ 0.054	1.341	+ 0.035	5.043	+ 0.089

With existing conditions the numerical model predicted an average annual deposition rate of 4.954 million tons in the J. Bennett Johnston Waterway between Lock and Dam No. 5 and the Interstate-220 bridge in Shreveport. Reducing bank erosion by 50 percent would reduce annual deposition in this reach by 0.035 million tons, and reducing bank erosion by 100 percent would reduce annual deposition in this reach by 0.082 million tons. If bank erosion rates have been underestimated by 100 percent then an additional 0.089 million tons would deposit in this reach annually. In the numerical model, reducing bank erosion results in an increase in channel degradation that somewhat offsets the benefit of bank protection.

Downstream from Lock and Dam No. 5

The numerical model was used to calculate sediment transport past Lock and Dam No. 5. Average annual sediment load was determined using the 20-year (1979-1999) hydrograph and is shown in Table 2. The table shows that the sediment load past Lock and Dam No. 5 would be reduced by 0.472 million tons per year if bank erosion was reduced by 50 percent, and that the sediment load would be reduced by 0.945 million tons per year if bank erosion was eliminated.

Table 2
Calculated Sediment Load Past Lock and Dam No. 5

	Total Outflow million tons/year	Sand Outflow million tons/year		Silt Outflow million tons/year		Clay Outflow million tons/year
Bank Erosion of 1.44 million tons/year		Very fine	2.753	Very fine	1.064	
		Fine	0.252	Fine	0.863	
		Medium	0.044	Medium	1.238	
		Coarse	0.001	Coarse	1.985	
	11.341	Total	3.050	Total	5.150	3.141
50 percent bank erosion		Very fine	2.612	Very fine	1.050	
		Fine	0.243	Fine	0.823	
		Medium	0.042	Medium	1.162	
		Coarse	0.001	Coarse	1.833	
	10.865	Total	2.898	Total	4.868	3.099
No bank erosion		Very fine	2.475	Very fine	1.036	
		Fine	0.233	Fine	0.782	
		Medium	0.040	Medium	1.088	
		Coarse	0.001	Coarse	1.684	
	10.397	Total	2.749	Total	4.590	3.058
200 percent bank erosion		Very fine	3.021	Very fine	1.091	
		Fine	0.273	Fine	0.944	
		Medium	0.049	Medium	1.386	
		Coarse	0.001	Coarse	2.282	
	12.271	Total	3.344	Total	5.703	3.224

Using the calculated sediment load past Lock and Dam No. 5, estimates of deposition in the Red River Waterway were made. The first estimate was made using measured sediment data from the Shreveport, LA (preproject river mile 77.2) and Alexandria, LA (preproject river mile 105) sediment gages. Concurrent measured sediment data by sediment size class were collected at these two gages in 1977 and 1978. These data represent preproject river conditions. Lindy C. Boggs Lock and Dam (Lock and Dam No. 1) and John H. Overton Lock and Dam (Lock and Dam No. 2) operate open river during the annual high flows that carry most of the river's sediment load. Lock and Dam No. 3 rarely goes into open river conditions, but uses a hinge pool operation that

enhances sediment transport. Russell B. Long Lock and Dam (Lock and Dam No. 4) and Joe D. Waggonner Jr. Lock and Dam (Lock and Dam No. 5) have high frequency pools and rarely go to open river conditions. Since the three downstream most pools pass most of the sediment load, an argument could be made that these preproject data can be used to provide an estimate for the existing condition percentage of deposition by size class. The data for measured sand load and total measured load are shown in Figures 17 and 18. The figures show that about 50 percent of the sand load was deposited between Alexandria and Shreveport, but that most of the fine load was not deposited. With this information, deposition in the Red River Waterway downstream from Lock and Dam No. 5 can be assumed to be 50 percent of the sand load. Using data from Table 2 it can be estimated that deposition in the waterway would be reduced by 0.076 million tons per year if bank erosion between Index and Arthur City was reduced by 50 percent, and 0.150 million tons per year if bank erosion between Index and Arthur City was eliminated.

A HEC-6W numerical model developed in 1987 (Copeland and Thomas 1988) to study the effects of river contraction dikes downstream from Lock and Dam No. 1 (Lindy C. Boggs Lock and Dam) was a second method used to estimate sediment deposition in the Red River Waterway downstream from Lock and Dam No. 5. Geometry for this model was based on the 1967-68 hydrographic survey of the Red River. The primary area of interest in the 1987 study was between Lock and Dam No. 1 (preproject river mile 46) and the confluence of the Red and Black Rivers (river mile 34). In this reach, cross sections were located at approximately one-half-mile intervals. Between Lock and Dam No. 1 and preproject river mile 140 the cross sections were located at approximately 2-mile intervals. Upstream from preproject river mile 140 cross-section intervals averaged 14 miles. This cross-section spacing makes the model inadequate for

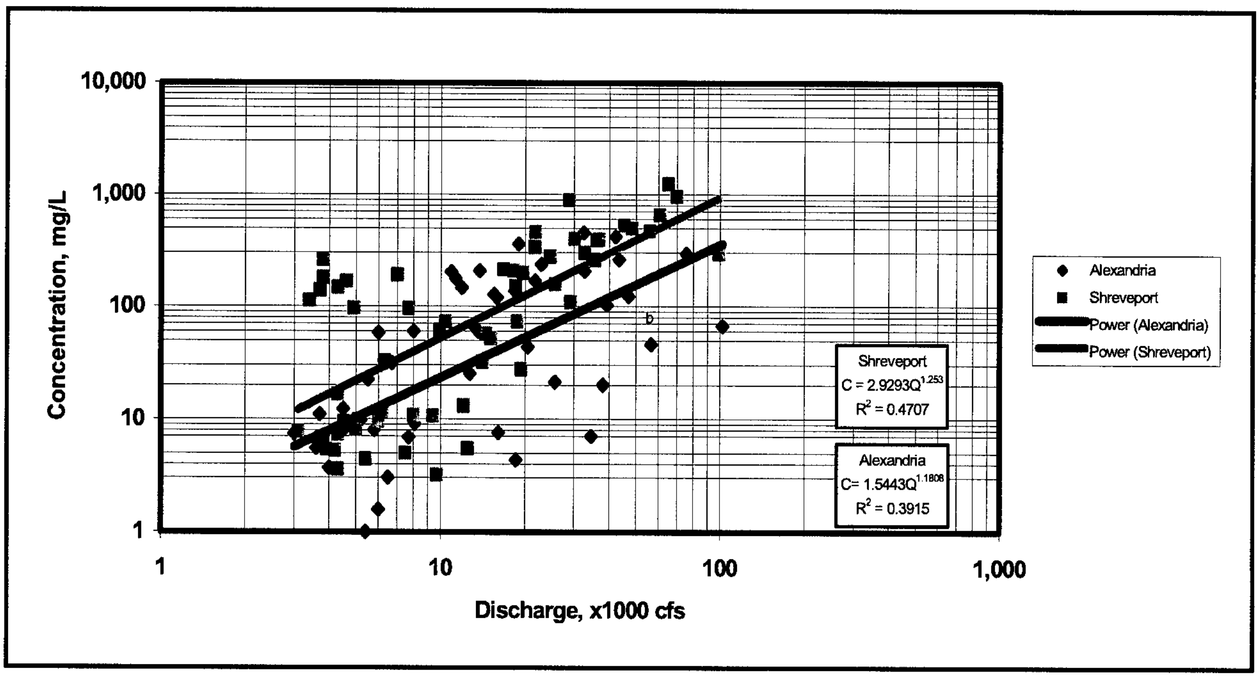

Figure 17. Measured sand concentration at Alexandria, LA, and Shreveport, LA, 1977-1978

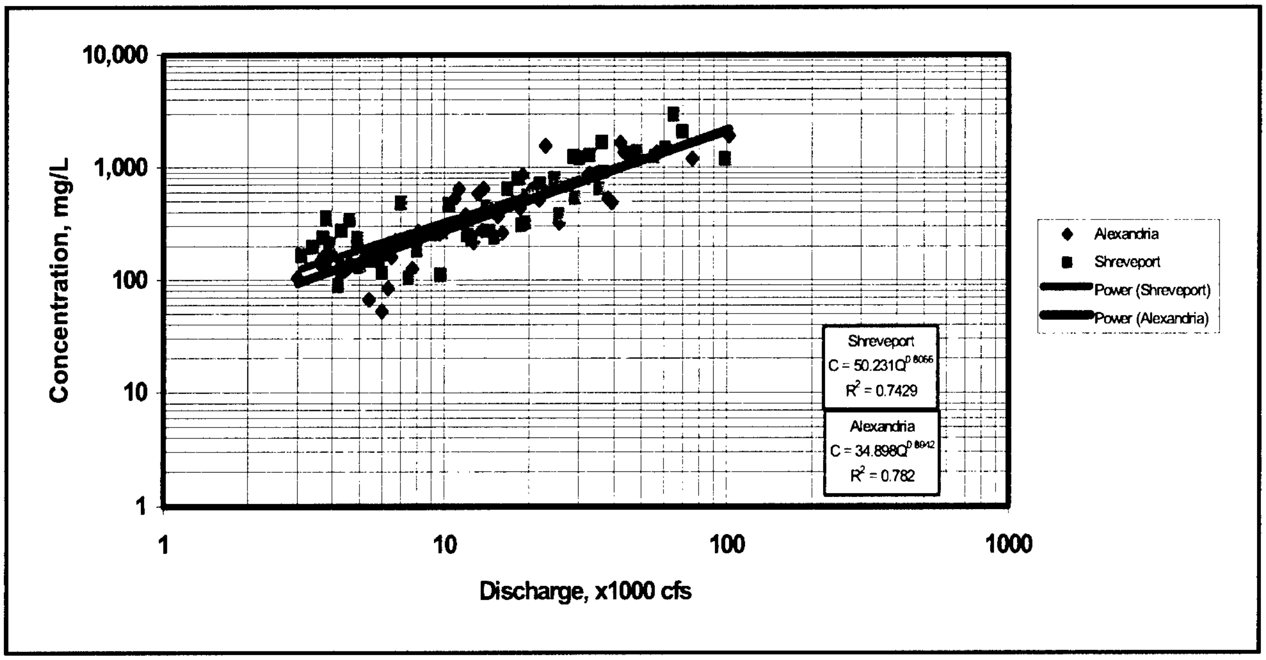

Figure 18. Measured total sediment concentration at Alexandria, LA, and Shreveport, LA, 1977-1978

determining the distribution of sediment deposition in the upper reaches of the waterway but is adequate for estimating the trap efficiency for each size class. Bed material gradations for the 1987 study were based on measured data collected at high flows and consisted entirely of sand. The 1975-1981 hydrograph used in the 1987 study was retained for the purpose of calculating trap efficiencies for each size class. The numerical model was updated to include the operation schedules at Lock and Dam No. 3 and Lock and Dam No. 4 (Russell B. Long Lock and Dam). Sediment inflow rating curves were calculated using output from the HEC-6W model between Lock and Dam No. 5 (Joe D. Waggonner Jr. Lock and Dam) and Arthur City.

Trap efficiencies for each size class were calculated using the 1987 HEC-6 model. Trap efficiencies for silts and clays were determined by comparing sediment transport quantities into and out of the model during the 15-year simulation. Trap efficiencies for sand size classes were determined by comparing sediment transport quantities into and out of deposition zones during the 15-year simulation. Only deposition zones were considered for calculating trap efficiency because considerable sediment was entrained from the riverbed in reaches where degradation was calculated. The net effect was more sand transported out of the model than supplied from upstream. Calculated trap efficiencies between Lock and Dam No. 5 and the confluence of the Black River for each size class are tabulated in Table 3. Using the tabulated percentages from Table 3 and the calculated sediment loads past Joe D. Waggonner Jr. Lock and Dam (Lock and Dam No. 5) shown in

Table 3
Size Class Trap Efficiency Calculated Using 1987 HEC-6 Model

Sediment Size Class	Percent
Clay	0
Very Fine Silt	1
Fine Silt	2
Medium Silt	16
Coarse Silt	24
Very Fine Sand	24
Fine Sand	98
Medium Sand	100
Coarse Sand	100

Table 2, sediment deposition for each size class was determined and is shown in Table 4.

Table 4
Calculated Deposition Between Lock and Dam No. 5 and Black River

	Total tons/year	Sand tons/year		Silt tons/year		Clay tons/year
Bank erosion of 1.40 million tons/year		Very fine	0.661	Very fine	0.011	
		Fine	0.247	Fine	0.017	
		Medium	0.044	Medium	0.198	
		Coarse	0.001	Coarse	0.476	
	1.655	Total	0.953	Total	0.702	0.000
50 percent bank erosion		Very fine	0.627	Very fine	0.011	
		Fine	0.238	Fine	0.016	
		Medium	0.042	Medium	0.186	
		Coarse	0.001	Coarse	0.440	
	1.561	Total	0.908	Total	0.653	0.000
No bank erosion		Very fine	0.594	Very fine	0.010	
		Fine	0.228	Fine	0.016	
		Medium	0.040	Medium	0.174	
		Coarse	0.001	Coarse	0.404	
	1.467	Total	0.863	Total	0.604	0.000
200 percent bank erosion		Very fine	0.725	Very fine	0.011	
		Fine	0.268	Fine	0.019	
		Medium	0.049	Medium	0.222	
		Coarse	0.001	Coarse	0.548	
	1.843	Total	1.043	Total	0.800	0.000

Using the 1987 HEC-6 numerical model, it was determined that annual deposition in the J. Bennett Johnston Waterway downstream from Joe D. Waggonner Jr. Lock and Dam due to sediment supplied from upstream for existing conditions would be about 1.655 million tons/year. Deposition could be reduced by 0.094 million tons if supply from bank erosion were reduced 50 percent and by 0.188 million tons if supply from bank erosion was eliminated. If bank erosion rates were underestimated by 100 percent then about 1.843 million tons/year would be deposited in the waterway downstream from Joe D. Waggonner Jr. Lock and Dam. Calculations using the 1987 HEC-6 model are about 25 percent higher than calculations using the Shreveport and Alexandria gage data. The 1987 HEC-6 results should be considered the more accurate results, but the gage data analysis provides support for the numerical results and provides a sense of the possible range in deposition rates in the waterway.

5 Conclusions and Recommendations

Reduction in Bank Erosion

The numerical model is adequate to evaluate the increase or decrease in the sediment transported into the Red River Waterway and to evaluate deposition in the waterway due to the increase or decrease in upstream bank erosion. The one-dimensional model predicts general aggradation and degradation and does not account for localized deposition and scour in backwater areas, lock approaches, or at hydraulic structures.

Interpretation of numerical model results must be made considering uncertainties associated with the boundary parameters. The numerical model adequately simulates sediment transport, but the model's predictive capabilities are limited by uncertainties related to the sediment measurements, tributary sediment inflow, volume of bank erosion, and the gradation of the eroded bank material. Annual bank erosion rates were assigned in the numerical model so that the combined contribution of sediment from the banks and the riverbed provided a reasonable quantity of sediment at Fulton. However, due to the poor channel definition from so few cross sections, the calculated degradation rate may be too high and the bank erosion rate too low.

With existing conditions the numerical model predicted an average annual deposition rate of 4.954 million tons in the J. Bennett Johnston Waterway between the Joe D. Waggonner Jr. Lock and Dam (Lock and Dam No. 5) and the I-220 bridge in Shreveport, LA. Reducing bank erosion by 50 percent would reduce annual deposition in this reach by 0.035 million tons, and reducing bank erosion by 100 percent would reduce annual deposition in this reach by 0.082 million tons. If bank erosion rates have been underestimated by 100 percent then an additional 0.089 million tons would deposit in this reach annually.

Using the 1987 HEC-6 numerical model, it was determined that annual deposition in the J. Bennett Johnston Waterway downstream from Joe D. Waggonner Jr. Lock and Dam due to sediment supplied from upstream for existing conditions would be about 1.655 million tons/year. Deposition could be reduced by 0.094 million tons if supply from bank erosion upstream from Index, AR, was reduced 50 percent and by 0.188 million tons if supply from bank erosion was eliminated. If bank erosion rates have been underestimated by

100 percent then about 1.843 million tons/year would be deposited in the waterway downstream from Joe D. Waggonner Jr. Lock and Dam. Calculations using the 1987 HEC-6 model are about 25 percent higher than calculations using the Shreveport, LA, and Alexandria, LA, gage data. The 1987 HEC-6 results should be considered the more accurate results, but the gage data analysis provides support for the numerical results and provides a sense of the possible range in deposition rates in the waterway.

Recommendations to Improve Numerical Model Predictions

The most significant uncertainties related to predictions from the numerical model are due to the sparse cross-section geometry. New cross-section surveys between Index and Arthur City are recommended. The cross sections should be spaced at about 2-mile increments to be consistent with increments in the model downstream, between Shreveport and Index. The survey should extend across the full width off the channel and include some floodplain elevations. The new survey should include the degradation ranges surveyed in 1969. Better definition of channel geometry would provide more certainty related to long-term degradation predictions. New surveys at the degradation ranges would provide geomorphic evidence of long-term degradation or aggradation trends.

Consideration should be given to incorporating Vicksburg District's 1993 hydrographic survey data of the Red River, between the Lower Old River Navigation Channel and Index, into the numerical model. These data could be used to provide better temporal consistency with new survey data upstream.

Bank material samples should be collected from the actively eroding banks along the Red River between Index and Arthur City. It is recommended that samples be collected from eroding banks at increments of at least 50 miles. The appropriate increment between samples should be determined in the field based on observed variability. If there is significant vertical variation in the bank gradation, samples should be collected from each stratum. The length of each stratum should also be measured. The gradation of the sediment supplied from the banks determines the distribution of the sediment deposition downstream.

It is recommended that sediment data be collected from the tributaries near their confluence with the Red River. In this study, sediment inflow from tributaries was assumed to be negligible. This assumption should be verified by obtaining tributary bed material samples and by calculating a sediment-inflow rating curve. Field investigations should be made to determine if there is evidence of channel incision or degradation between the dams and the Red River.

It is recommended that a sediment data collection program be reinstated at Arthur City. Sufficient data should be collected to determine if there has been a shift in the sediment rating curve since 1978. The data should be collected using standardized sediment samplers and particle size distributions should be determined.

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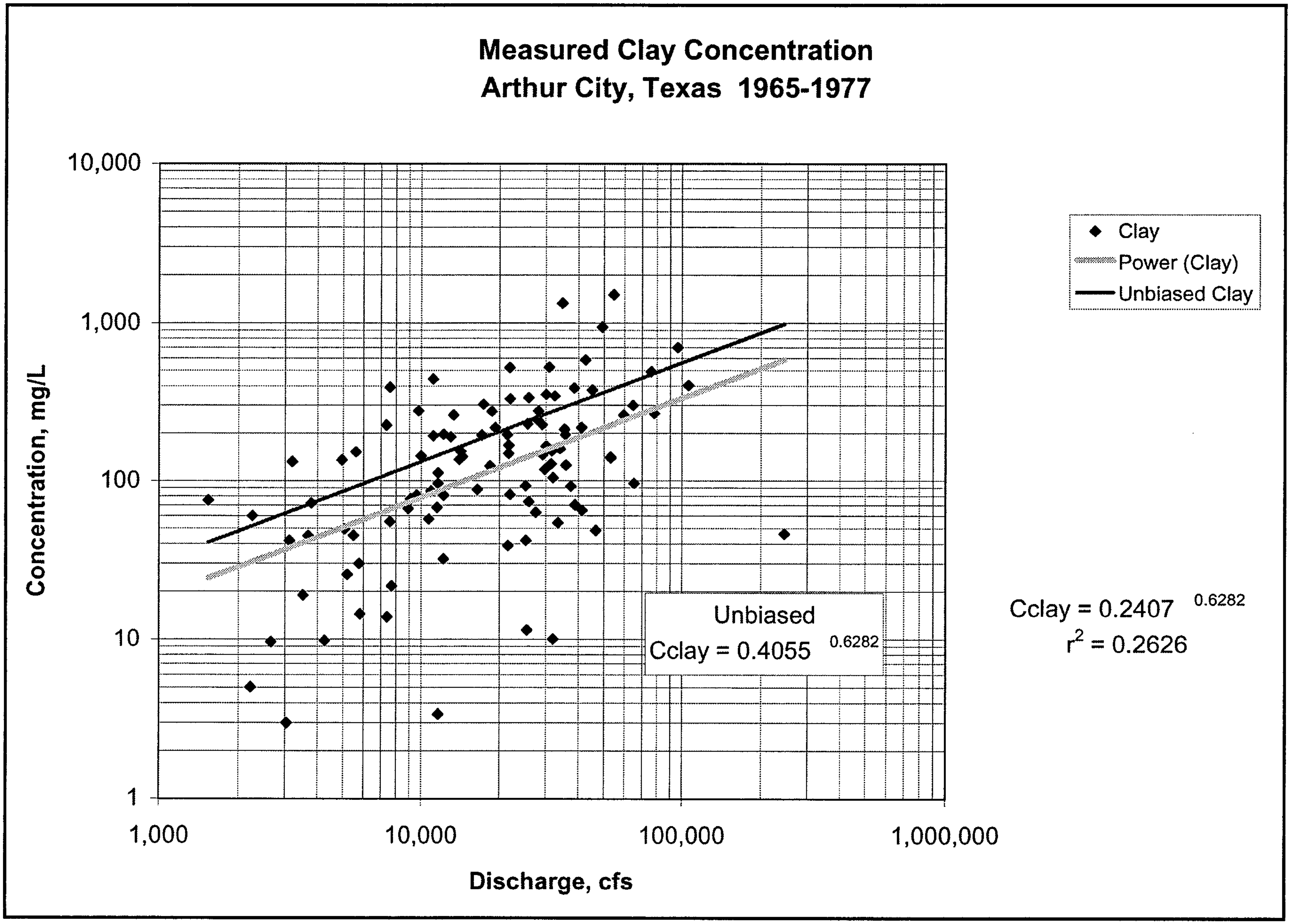
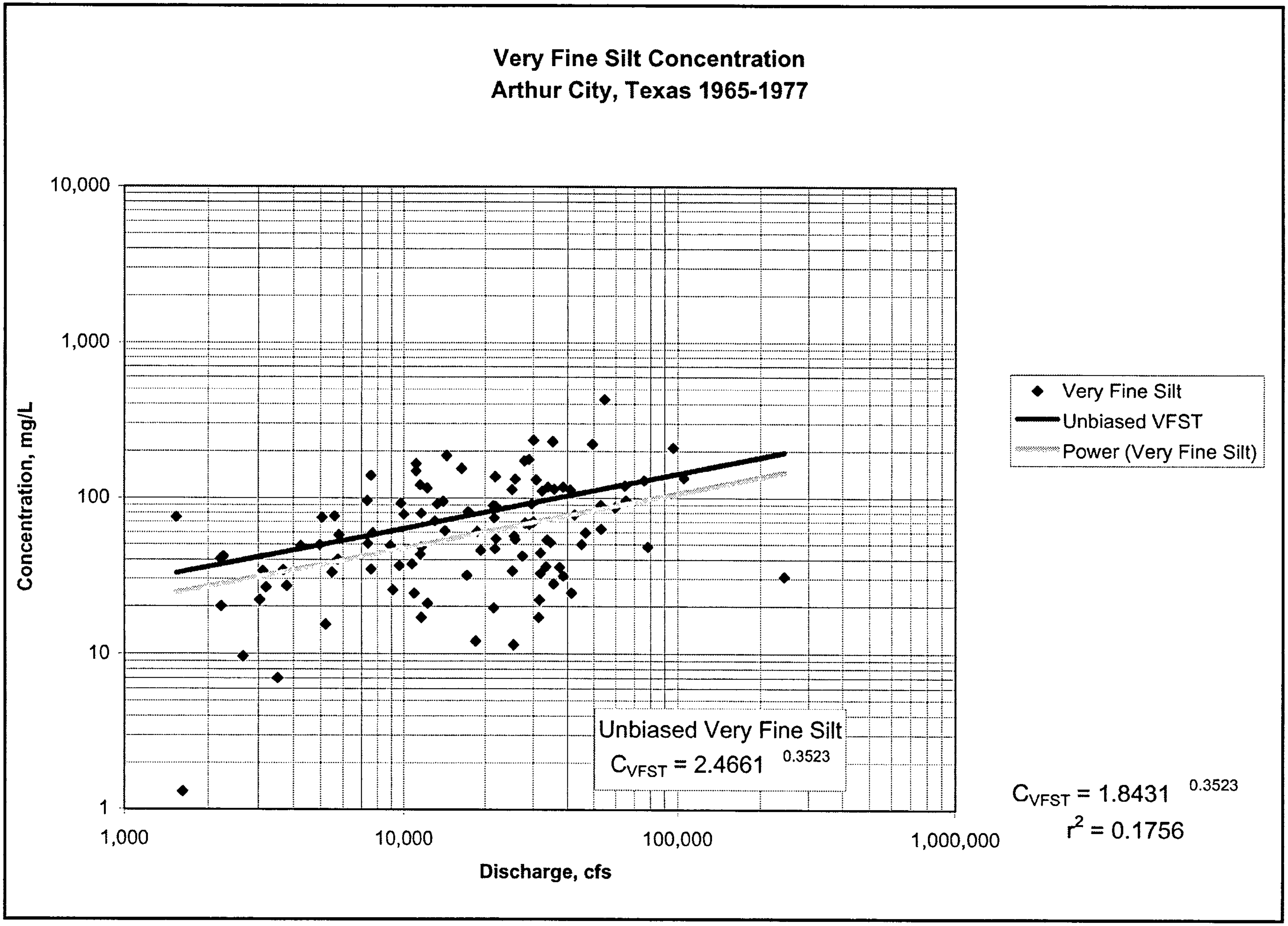


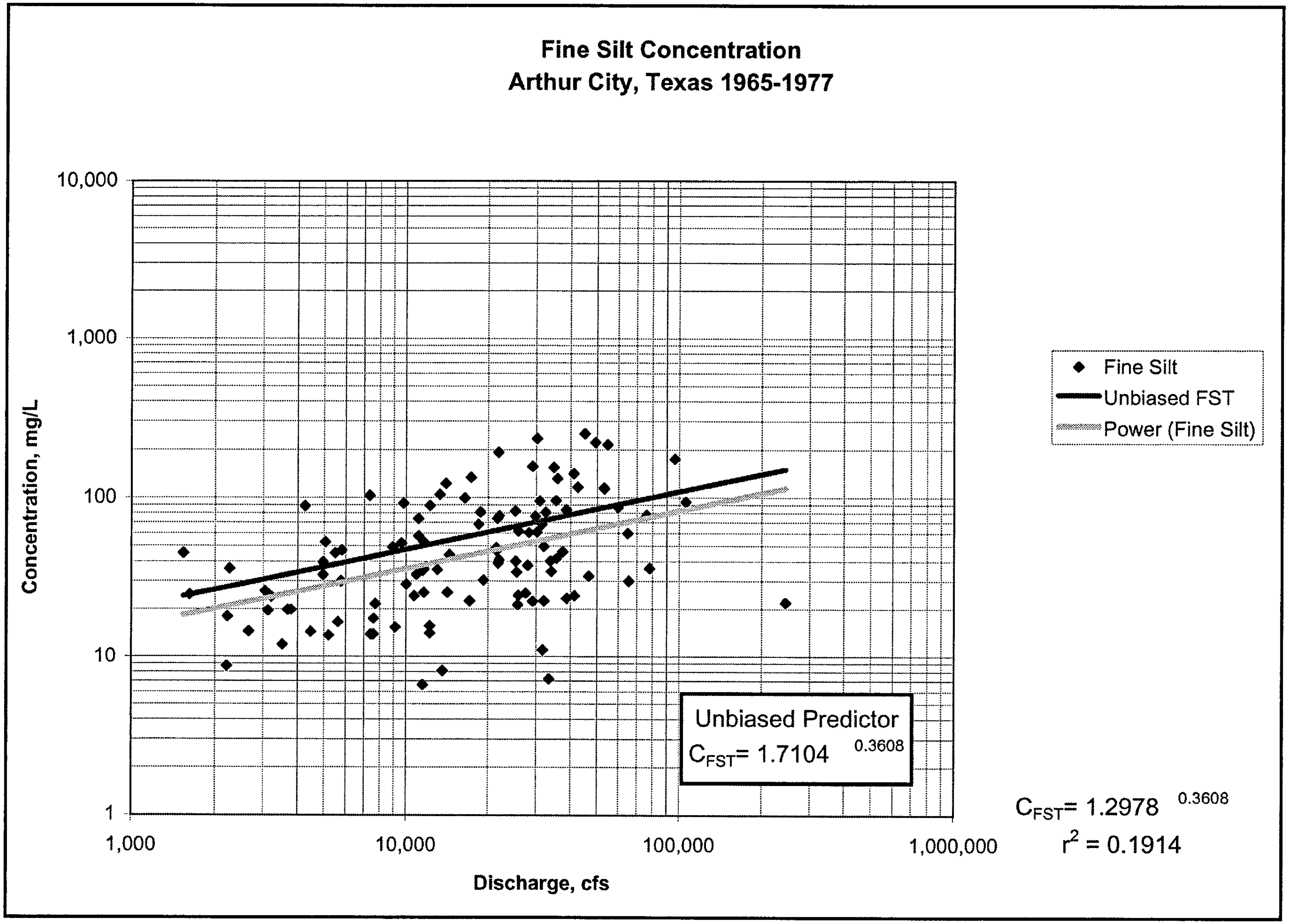
Measured Clay Concentration
Arthur City, Texas 1965-1977
Concentration, mg/L
10,000
1,000
100
10
1
1,000
10,000
100,000
1,000,000
Discharge, cfs
Clay
Power (Clay)
Unbiased Clay
Unbiased
Cclay = 0.4055 0.6282
Cclay = 0.2407 0.6282
r2 = 0.2626

Plate 1

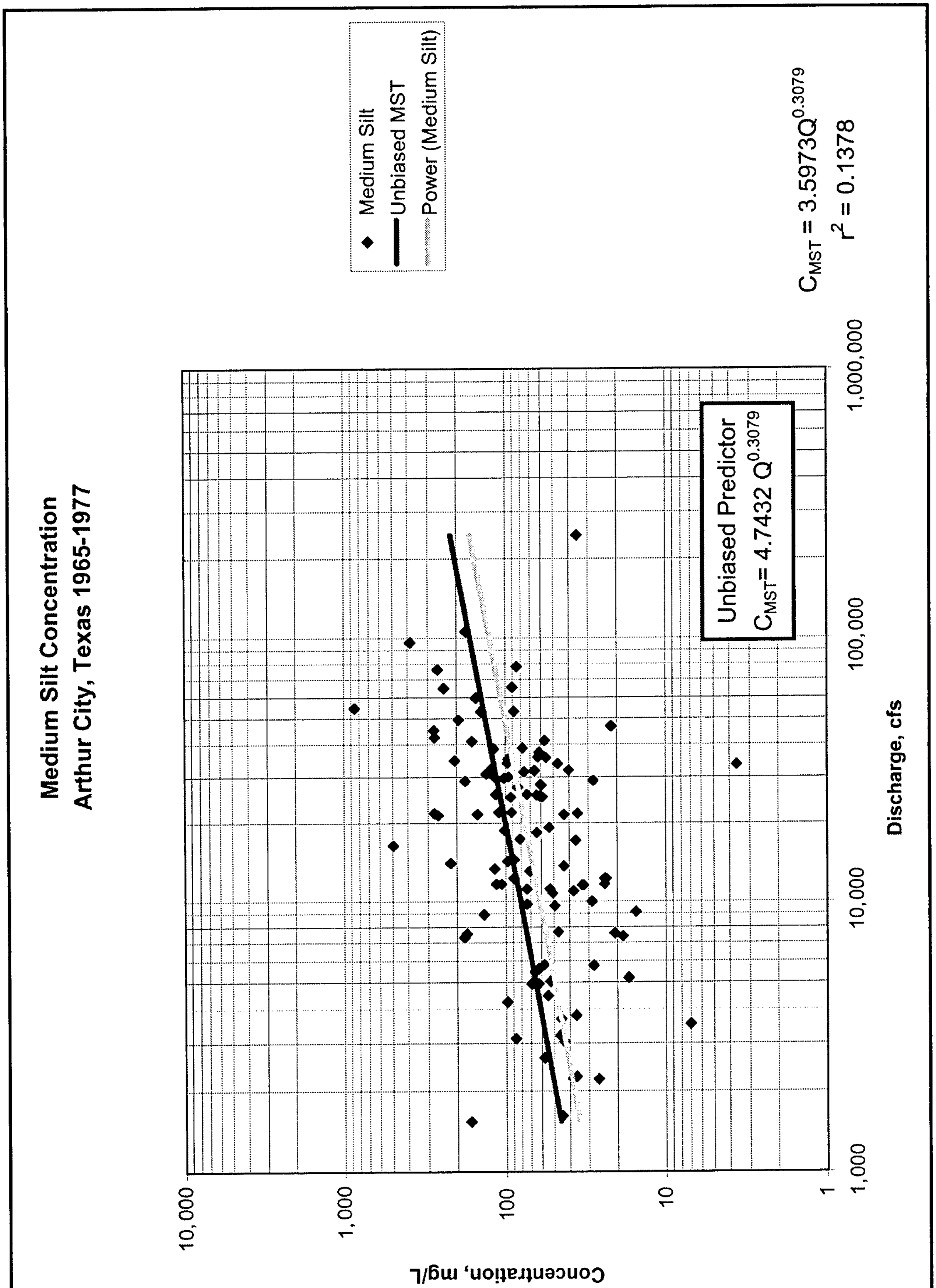
Plate 2



Very Fine Silt Concentration
Arthur City, Texas 1965-1977
Concentration, mg/L
10,000
1,000
100
10
1
1,000
10,000
100,000
1,000,000
Discharge, cfs
Very Fine Silt
Unbiased VFST
Power (Very Fine Silt)
Unbiased Very Fine Silt
$C_{VFST} = 2.4661^{0.3523}$
$C_{VFST} = 1.8431^{0.3523}$
$r^2 = 0.1756$

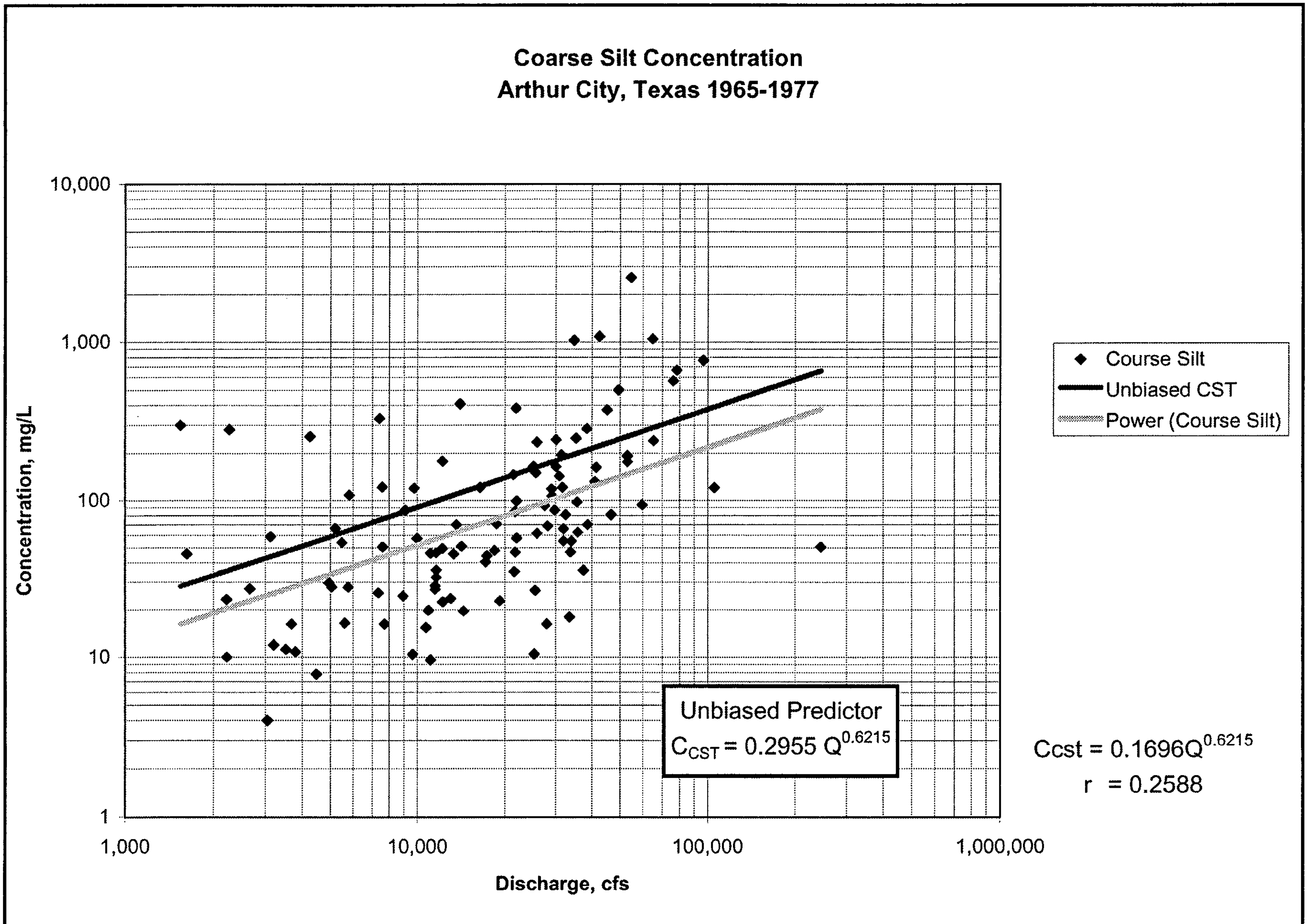


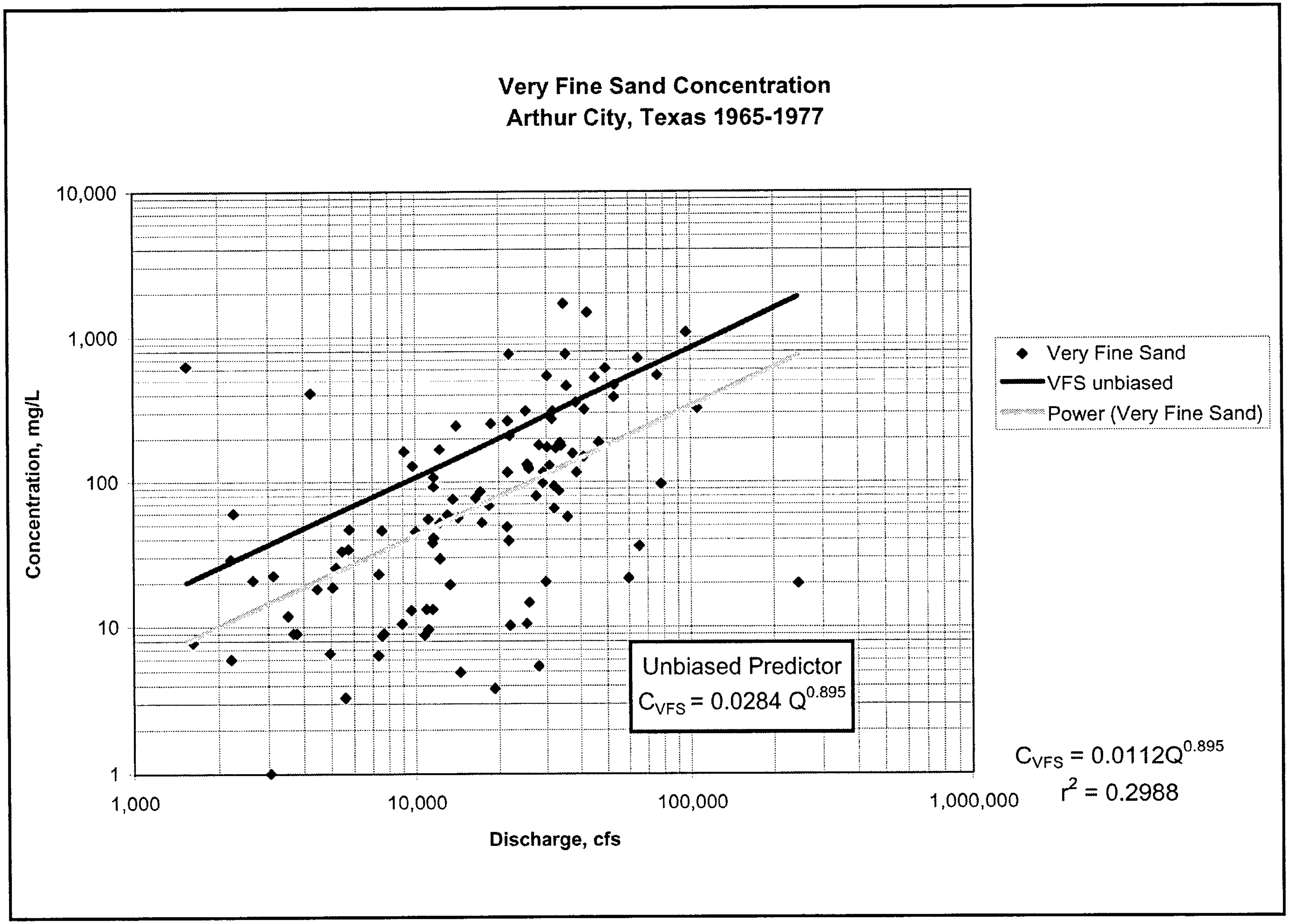
Fine Silt Concentration
Arthur City, Texas 1965-1977
Concentration, mg/L
10,000
1,000
100
10
1
1,000
10,000
100,000
1,000,000
Discharge, cfs
Fine Silt
Unbiased FST
Power (Fine Silt)
Unbiased Predictor
$C_{FST} = 1.7104\ ^{0.3608}$
$C_{FST} = 1.2978\ ^{0.3608}$
$r^2 = 0.1914$



Medium Silt Concentration
Arthur City, Texas 1965-1977
Medium Silt
Unbiased MST
Power (Medium Silt)
Unbiased Predictor
$C_{MST} = 4.7432\ Q^{0.3079}$
$C_{MST} = 3.5973Q^{0.3079}$
$r^2 = 0.1378$
Concentration, mg/L
Discharge, cfs
10,000
1,000
100
10
1
1,000
10,000
100,000
1,000,000

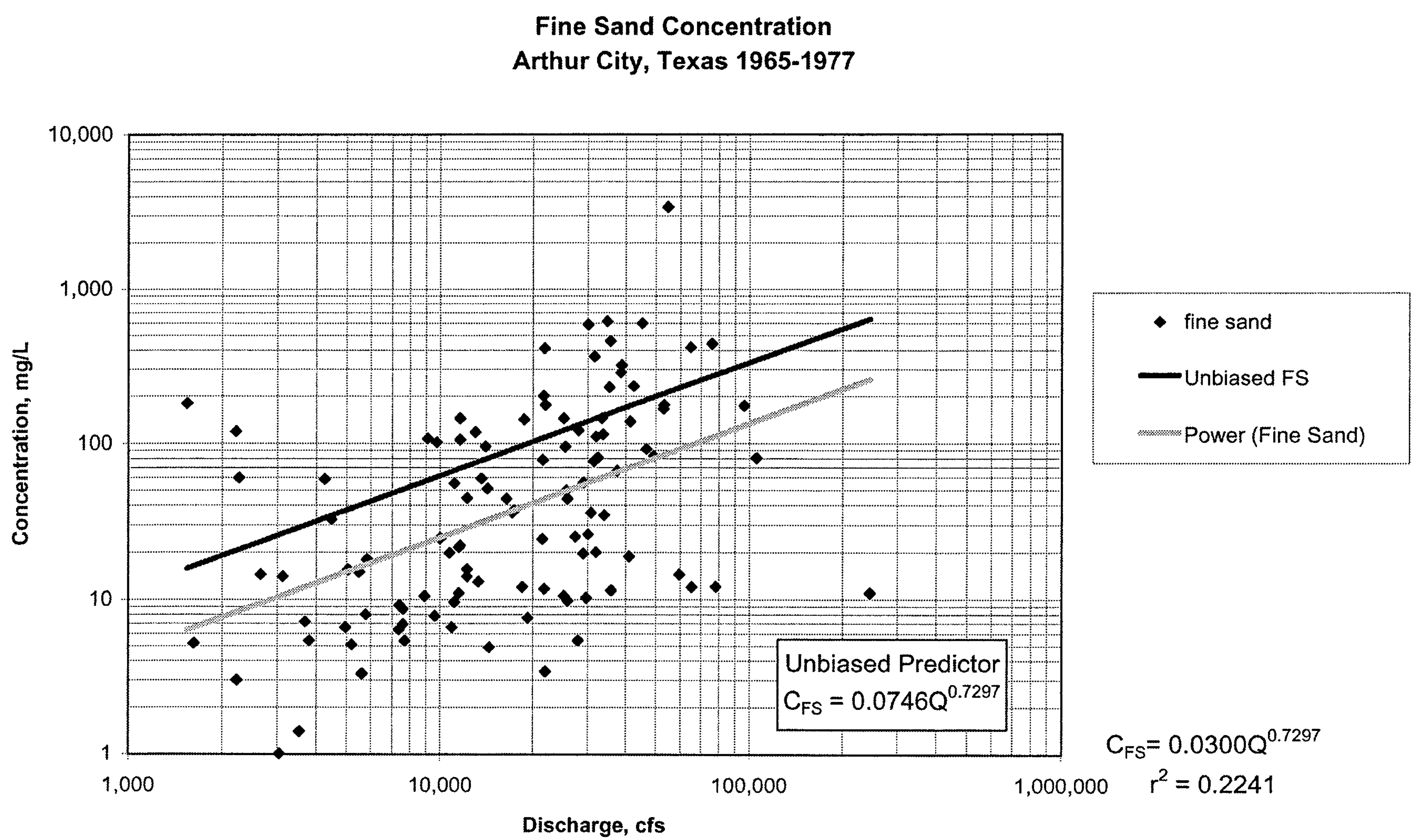
Plate 4


Coarse Silt Concentration
Arthur City, Texas 1965-1977
Concentration, mg/L
10,000
1,000
100
10
1
1,000
10,000
100,000
1,000,000
Discharge, cfs
Course Silt
Unbiased CST
Power (Course Silt)
Unbiased Predictor
C_CST = 0.2955 Q^0.6215
Ccst = 0.1696Q^0.6215
r = 0.2588



Very Fine Sand Concentration
Arthur City, Texas 1965-1977
10,000
1,000
100
10
1
Concentration, mg/L
1,000
10,000
100,000
1,000,000
Discharge, cfs
Very Fine Sand
VFS unbiased
Power (Very Fine Sand)
Unbiased Predictor
$C_{VFS} = 0.0284\ Q^{0.895}$
$C_{VFS} = 0.0112Q^{0.895}$
$r^2 = 0.2988$

Plate 6



Fine Sand Concentration
Arthur City, Texas 1965-1977
Concentration, mg/L
10,000
1,000
100
10
1
1,000
10,000
100,000
1,000,000
Discharge, cfs
fine sand
Unbiased FS
Power (Fine Sand)
Unbiased Predictor
$C_{FS} = 0.0746Q^{0.7297}$
$C_{FS} = 0.0300Q^{0.7297}$
$r^2 = 0.2241$

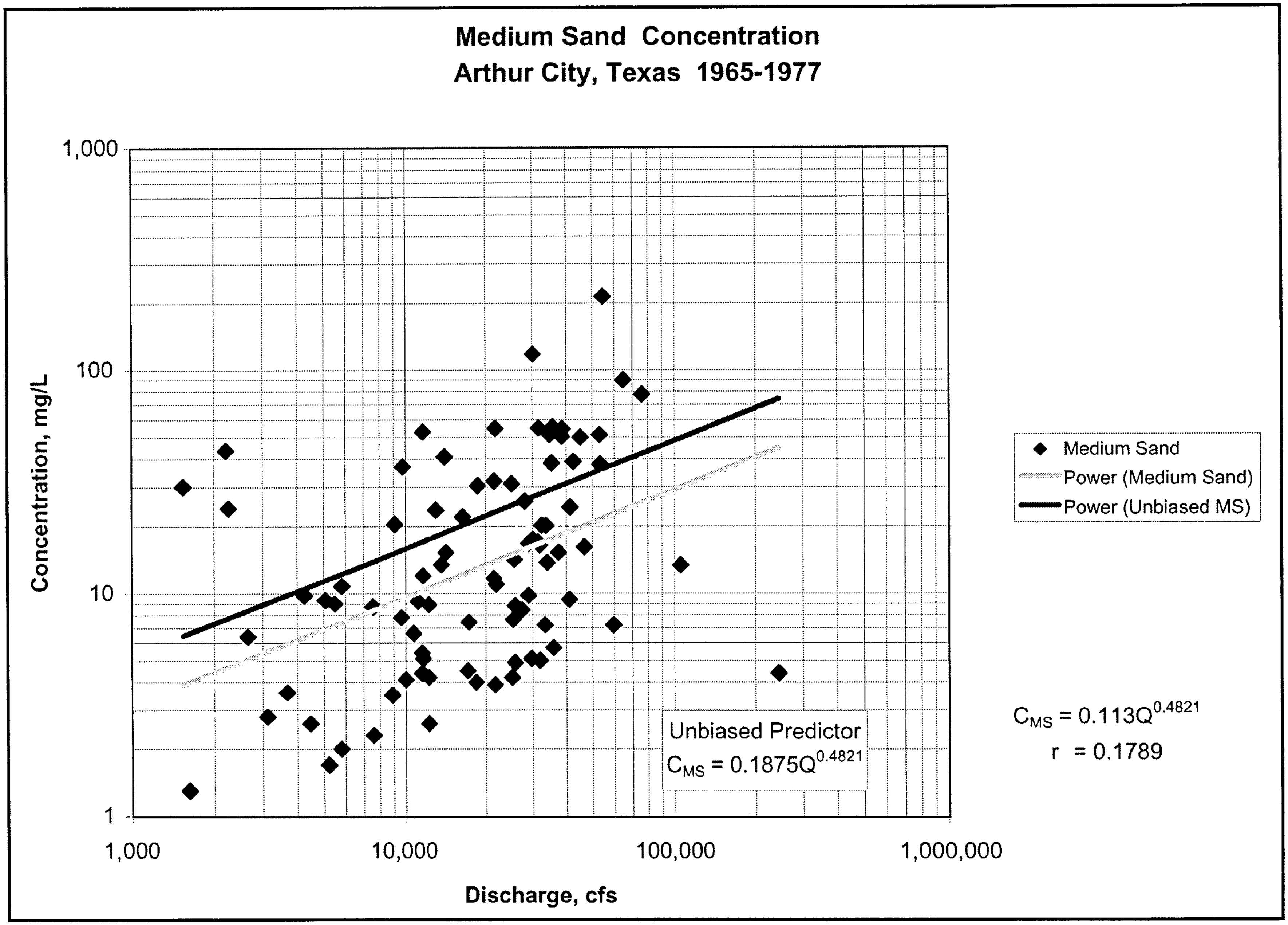

Medium Sand Concentration
Arthur City, Texas 1965-1977
1,000
100
10
1
Concentration, mg/L
1,000
10,000
100,000
1,000,000
Discharge, cfs
Medium Sand
Power (Medium Sand)
Power (Unbiased MS)
Unbiased Predictor
$C_{MS} = 0.1875Q^{0.4821}$
$C_{MS} = 0.113Q^{0.4821}$
$r = 0.1789$

Plate 8

Appendix A
Measured Sediment Data

Table A1
Red River Sediment Measurements, Arthur City, TX

Blumer (1983)

Date	Discharge cfs	Total Concentration	Percent Finer Than 0.5 mm	0.25 mm	0.125 mm	0.062 mm	0.032 mm	0.016 mm	0.008 mm	0.004 mm
4/23/1958	14,000	1360	100	97	90	72	42	26	17	10
2/11/1965	35,300	1910	100	98	86	46	33	28	23	11
2/25/1965	3,520	70	100	99	97	80	64	54	37	27
3/4/1965	5,480	300	100	97	92	81	63	41	26	15
5/11/1965	9,750	920	100	96	85	71	58	50	40	30
5/13/1965	9,980	410	100	99	93	82	68	61	54	35
2/10/1966	21,800	2740	100	98	83	55	41	31	24	19
2/16/1966	9,100	510	100	96	75	43	26	23	20	15
3/16/1966	2,260	600	100	96	86	76	29	23	17	10
4/26/1966	45,100	2500	100	98	74	53	38	27	17	15
5/2/1966	53,000	1280	100	96	83	53	38	27	18	11
5/5/1966	27,400	420	100	98	92	73	51	31	25	15
3/29/1967	1,540	1500	100	98	86	44	24	13	10	5
4/14/1967	14,400	490	100	100	99	98	94	76	67	29
4/16/1967	21,400	810	100	100	97	91	73	41	35	24
4/17/1967	21,900	340	100	100	99	96	79	52	40	24
4/22/1967	49,300	2770	100	100	97	75	57	50	42	34
5/23/1967	7,340	640	100	100	99	98	94	66	50	35
6/2/1967	30,800	1190	100	100	97	86	74	63	55	44
9/11/1967	16,400	1100	100	98	94	87	76	31	22	8
9/20/1967	9,610	260	99	96	93	88	84	65	45	31
1/30/1968	27,900	540	100	100	99	98	95	84	77	45
2/2/1968	19,200	380	100	100	98	97	91	77	69	57
2/7/1968	3,680	180	100	98	94	89	80	55	44	25
3/14/1968	21,900	1100	100	99	83	64	55	45	38	30
3/23/1968	38,500	1680	100	97	80	59	42	35	30	23
3/24/1968	33,700	670	100	97	80	52	45	38	32	24
3/28/1968	14,200	510	100	97	87	76	66	47	42	30
3/29/1968	7,390	460	100	100	98	93	21	17	14	3
4/3/1968	35,800	570	100	99	97	87	76	65	42	22
4/10/1968	8,910	350	100	99	96	93	86	47	33	19
4/25/1968	25,800	490	100	99	97	94	46	31	26	15
5/1/1968	10,900	220	100	100	97	91	82	65	50	39
5/7/1968	4,250	980	100	99	93	51	25	15	6	1
5/16/1968	31,900	250	100	98	90	64	42	26	17	4
5/18/1968	78,100	1210	100	100	99	91	36	29	26	22

(Sheet 1 of 3)

Note: Original data percentage only in AurthurData.xls.

Table A1 (Continued)

Blumer (1983)

Date	Discharge cfs	Total Concentration	Percent Finer Than 0.5 mm	0.25 mm	0.125 mm	0.062 mm	0.032 mm	0.016 mm	0.008 mm	0.004 mm
5/19/1968	65,300	600	100	100	98	92	52	37	32	16
5/21/1968	34,000	690	100	98	93	67	59	45	40	23
5/23/1968	41,300	810	100	97	80	41	21	14	11	8
5/27/1968	31,400	850	100	98	89	57	34	25	17	15
6/5/1968	244,600	220	100	98	93	84	61	45	35	21
6/18/1968	13,300	650	100	100	98	95	88	70	54	40
6/27/1968	25,600	710	100	98	91	73	52	43	40	32
7/1/1968	3,790	180	100	100	97	92	86	66	55	40
7/9/1968	2,220	100	100	100	97	91	81	43	25	5
7/29/1968	7,570	870	100	99	98	97	83	63	61	45
10/11/1968	11,600	660	98	90	74	60	53	37	29	17
10/18/1968	4,950	330	100	100	98	96	87	66	56	41
10/31/1968	5,810	360	100	97	92	79	49	33	20	4
11/5/1968	3,200	240	100	100	100	100	95	76	66	55
11/19/1968	3,120	280	100	99	94	86	65	34	27	15
12/5/1968	7,690	180	100	100	97	92	83	57	45	12
12/16/1968	3,040	100	100	100	99	98	94	51	25	3
1/6/1969	4,470	130	100	98	73	59	53	11	0	0
1/21/1969	7,580	230	100	99	96	76	54	45	39	24
2/18/1969	11,600	600	99	97	73	55	49	30	24	16
2/24/1969	35,600	1390	100	96	63	30	23	19	16	14
3/10/1969	17,100	450	100	99	91	72	63	55	50	43
4/1/1969	10,700	220	100	97	88	84	77	54	43	26
4/9/1969	11,600	170	100	97	84	60	41	27	12	2
4/21/1969	13,000	590	100	96	76	66	62	50	44	32
4/30/1969	31,600	1100	100	95	62	34	23	17	16	14
5/7/1969	64,700	2990	100	97	83	59	24	16	14	10
5/8/1969	76,000	2590	100	97	80	59	37	27	24	19
5/22/1969	46,600	540	100	97	80	45	30	26	20	9
5/29/1969	30,100	2340	100	95	70	47	40	35	25	15
6/3/1969	12,200	260	100	99	93	73	54	45	39	31
6/14/1969	25,200	210	100	98	93	88	83	55	36	20
6/18/1969	5,770	200	100	99	95	78	64	50	35	15
6/23/1969	5,200	170	100	99	96	81	42	32	24	15
10/14/1969	12,200	890	100	99	94	75	55	45	35	22
10/18/1969	4,950	330	100	100	98	96	87	68	56	41
2/4/1970	11,100	920	100	99	93	87	82	74	66	48

(Sheet 2 of 3)

Table A1 (Concluded)										
Blumer (1983)										
Date	Discharge cfs	Total Concentration	Percent Finer Than							
			0.5 mm	0.25 mm	0.125 mm	0.062 mm	0.032 mm	0.016 mm	0.008 mm	0.004 mm
2/17/1970	5,610	330	100	100	99	98	93	74	69	46
3/5/1970	18,700	1010	100	97	83	58	51	41	33	27
4/23/1970	11,100	480	100	100	98	96	94	83	71	40
4/28/1970	25,800	880	100	99	94	80	73	60	53	38
5/6/1970	11,500	220	99	97	92	86	73	58	55	0
5/22/1970	2,210	290	100	85	44	34	26	17	14	0
6/2/1970	2,650	160	100	96	87	74	57	21	12	6
9/21/1970	5,060	310	97	94	89	83	74	57	40	16
10/12/1970	21,600	1060	97	94	75	50	42	28	21	14
10/14/1970	25,100	1030	100	97	83	53	37	28	20	9
4/23/1971	17,300	740	100	99	94	87	81	70	52	41
10/20/1971	29,000	980	100	99	97	87	75	57	41	23
10/22/1971	30,100	870	98	96	93	73	45	34	27	19
12/10/1971	96,300	3490	100	100	95	64	42	31	26	20
12/11/1971	105,600	1340	100	99	93	69	60	47	40	30
12/12/1971	59,600	720	100	99	97	94	81	60	48	36
12/16/1971	29,100	560	100	97	87	66	47	42	38	26
11/1/1972	41,000	940	100	99	97	81	67	50	35	23
11/3/1972	29,700	510	100	99	97	93	76	56	41	23
11/4/1972	21,700	390	100	99	96	86	74	65	55	43
11/9/1972	18,400	400	100	99	96	79	67	51	34	31
11/16/1972	11,500	270	100	98	90	76	66	54	41	25
2/9/1973	32,400	1010	100	98	90	73	65	53	45	34
2/12/1973	21,500	390	100	97	77	47	38	27	15	10
2/15/1973	13,600	270	100	95	73	45	19	3	0	0
10/18/1973	25,400	380	100	98	73	38	31	15	6	3
10/26/1973	12,200	140	100	97	87	66	50	33	23	23
11/1/1973	28,100	860	100	97	83	62	54	47	40	32
12/3/1973	53,100	1260	100	97	83	46	32	25	16	11
12/5/1973	37,400	510	100	97	84	53	46	34	25	18
5/7/1974	38,700	780	98	91	50	35	26	16	13	9
6/11/1974	31,900	550	100	97	77	60	48	36	27	19
6/13/1974	33,400	360	99	97	57	33	28	27	25	15
4/23/1976	34,700	5130	100	99	87	54	34	30	27	26
3/31/1977	54,600	21400	100	99	83	26	14	10	9	7
6/2/1977	42,400	3880	100	99	93	55	27	20	17	15
(Sheet 3 of 3)										

Table A2
Suspended Sediment -- Measured Data, Fulton, AR

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment	Suspended Sediment: Sieve Diameter		Sand				
					ppm	Finer Than 0.062 mm ppm	Greater Than 0.062 mm ppm	Very Fine 0.063 mm - 0.125 mm ppm	Fine 1.250 mm - 0.250 mm ppm	Medium 0.250 mm - 0.500 mm ppm	Coarse 0.500 mm - 1.000 mm ppm	Very Coarse 1.000 mm - 2.000 mm ppm
1/16/84	9,310	367	2.56	38.0	127.8	86.3	41.5	---	---	---	---	---
3/19/84	36,300	520	4.81	56.0	347.5	161.8	185.8	---	---	---	---	---
5/14/84	32,000	532	3.75	73.0	99.5	92.8	6.8	---	---	---	---	---
7/23/84	3,250	381	0.88	84.0	66.5	61.5	5.0	---	---	---	---	---
9/17/84	2,580	366	0.74	73.0	90.5	74.5	16.0	---	---	---	---	---
2/11/85	21,200	492	3.79	38.0	---	---	---	---	---	---	---	---
3/15/85	39,800	543	4.07	58.0	350.8	310.5	40.3	---	---	---	---	---
3/29/85	71,400	557	5.87	67.0	---	---	---	---	---	---	---	---
5/10/85	68,800	557	5.66	73.0	326.5	253.8	72.8	---	---	---	---	---
5/24/85	34,900	532	4.11	74.0	---	---	---	---	---	---	---	---
6/7/85	12,100	420	2.30	84.0	---	---	---	---	---	---	---	---
6/21/85	54,500	545	5.21	80.0	---	---	---	---	---	---	---	---
7/12/85	10,000	395	2.07	84.0	280.0	223.0	57.0	---	---	---	---	---
7/26/85	5,570	381	1.35	85.0	---	---	---	---	---	---	---	---
8/9/85	4,470	381	1.10	91.0	---	---	---	---	---	---	---	---
8/23/85	4,280	381	1.16	81.0	97.5	85.3	12.3	---	---	---	---	---
9/6/85	7,360	395	1.70	82.0	---	---	---	---	---	---	---	---
9/21/85	2,210	361	0.72	77.0	---	---	---	---	---	---	---	---
10/25/85	14,200	428	2.67	72.0	1565.8	993.3	572.5	---	---	---	---	---
11/8/85	12,190	410	2.72	60.0	---	---	---	---	---	---	---	---
11/22/85	39,800	515	5.05	59.0	---	---	---	---	---	---	---	---
12/6/85	46,710	539	4.77	48.0	---	---	---	---	---	---	---	---

(Sheet 1 of 9)

Table A2 (Continued)

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment ppm	Sieve Diameter Finer Than 0.062 mm ppm	Sieve Diameter Greater Than 0.062 mm ppm	Sand Very Fine 0.063 mm - 0.125 mm ppm	Sand Fine 1.250 mm - 0.250 mm ppm	Sand Medium 0.250 mm - 0.500 mm ppm	Sand Coarse 0.500 mm - 1.000 mm ppm	Sand Very Coarse 1.000 mm - 2.000 mm ppm
2/13/87	20,200	502	2.96	42.0	---	---	---	---	---	---	---	---
3/27/87	54,500	542	4.89	52.0	---	---	---	---	---	---	---	---
4/24/87	7,670	430	1.48	69.0	222.0	186.5	35.5	---	---	---	---	---
5/8/87	4,700	410	1.01	70.0	---	---	---	---	---	---	---	---
7/10/87	45,700	527	4.74	81.0	---	---	---	---	---	---	---	---
9/11/87	6,930	450	1.60	80.0	---	---	---	---	---	---	---	---
12/10/87	19,000	517	2.87	54.0	476.0	306.0	170.0	---	---	---	---	---
5/12/88	9,080	500	1.79	81.0	---	---	---	---	---	---	---	---
5/20/88	5,760	381	1.48	66.0	---	---	---	---	---	---	---	---
5/26/88	4,550	381	1.22	81.0	---	---	---	---	---	---	---	---
6/2/88	2,980	349	0.92	78.0	74.3	17.8	56.5	---	---	---	---	---
6/9/88	3,470	376	0.98	72.0	---	---	---	---	---	---	---	---
9/8/88	7,440	405	2.00	76.0	392.5	181.5	211.5	127.3	72.3	6.3	4.6	---
9/15/88	2,930	363	1.22	84.0	164.0	69.8	94.3	39.8	43.7	6.9	4.3	---
9/22/88	1,690	359	0.79	87.0	317.2	216.5	102.0	53	42.6	5.7	0.6	---
10/13/88	2,790	365	1.18	70.0	119.2	109.5	9.7	3.9	3.3	1.7	0.8	---
10/20/88	3,120	368	1.26	73.0	34.7	23.2	11.5	4.9	3.6	1.6	1.4	---
10/27/88	3,450	368	1.37	67.0	144.2	73.2	71.0	59.3	9.4	2.3	---	---
11/10/88	3,520	369	1.34	71.0	871.2	580.2	291.0	187.4	96.9	6.4	0.3	---
11/17/88	3,520	369	1.33	71.0	1792.0	873.8	918.2	498.6	347.1	68.9	3.7	---
12/1/88	23,800	506	3.69	48.0	699.2	90.0	609.2	176.7	377.7	54.8	---	---
12/15/88	6,980	409	1.74	48.0	240.7	201.2	39.5	15.6	10.2	13.1	0.6	---
12/22/88	4,410	405	1.27	58.0	52.8	37.3	15.5	---	---	---	---	---
12/29/88	10,700	486	2.20	43.0	77.0	63.5	13.5	6.2	5.6	1.2	0.38	---

(Sheet 2 of 9)

Table A2 (Continued)

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment			Sand				
						Sieve Diameter						
					ppm	Finer Than 0.062 mm ppm	Greater Than 0.062 mm ppm	Very Fine 0.063 mm - 0.125 mm ppm	Fine 1.250 mm - 0.250 mm ppm	Medium 0.250 mm - 0.500 mm ppm	Coarse 0.500 mm - 1.000 mm ppm	Very Coarse 1.000 mm - 2.000 mm ppm
1/12/89	6,140	381	1.50	65.0	411.5	65.3	346.2	5.5	141.3	199.1	0.3	---
1/19/89	14,000	495	2.41	64.0	327.5	91.0	236.5	17.0	39.7	172.3	7.1	---
3/2/89	40,800	532	4.00	60.0	87.0	65.5	21.5	12.9	2.9	5.4	0.26	---
4/27/89	10,400	433	1.93	60.0	518.3	149.3	369.0	253.0	94.5	13.3	8.5	---
5/3/89	12,100	445	2.12	62.0	50.8	31.5	19.2	12.3	3.96	1.85	1.1	---
5/11/89	22,900	501	3.20	66.0	1058.5	847.3	211.2	136.3	59.5	4.96	10.5	---
5/18/89	54,400	513	5.23	63.0	6169.0	2936.5	3232.5	2744.4	436.4	22.6	29.1	---
5/20/89	84,100	547	6.66	77.0	2168.0	1490.0	753.0	534.6	195.8	22.3	---	---
5/21/89	67,100	542	5.76	77.0	1409.3	991.5	417.8	308.7	82.3	22.6	4.1	---
6/22/89	64,400	524	5.55	78.0	332.0	302.0	29.5	26.0	3.5	---	---	---
7/3/89	53,900	537	5.23	80.0	633.0	593.8	39.3	34.1	2.6	2.6	---	---
7/18/89	45,000	514	4.75	80.0	416.8	299.8	117.0	99.8	13.1	4.0	---	---
8/3/89	16,200	495	2.55	80.0	437.8	172.8	265.0	112.1	135.7	16.4	0.8	---
8/9/1989	15,500	492	2.61	78.0	60.0	48.5	11.5	1.3	4.5	5.6	0.1	---
8/18/89	12,900	455	2.62	79.0	59.7	58.5	1.2	0.7	0.5	---	---	---
8/24/89	12,000	468	2.18	82.0	530.8	109.3	421.5	236.7	155.1	29.2	0.5	---
8/31/89	11,600	460	2.21	82.0	134.5	126.0	8.5	6.9	0.5	1.1	---	---
9/7/89	6,230	370	1.50	81.0	399.3	187.0	212.3	188.7	18.2	1.5	3.9	---
9/14/89	9,440	433	2.06	76.0	115.8	102.3	13.5	10.6	1.9	0.9	---	---
9/21/89	21,200	499	3.52	78.0	68.8	59.5	9.3	6.7	2.2	0.4	---	---
10/5/89	11,000	444	2.42	77.0	768.0	135.5	632.5	373.8	214.4	8.1	36.4	---
10/12/89	6,220	361	1.51	70.0	19.3	13.3	6.0	1.8	1.7	1.5	1.0	---
10/18/89	4,810	357	1.48	72.0	14.5	11.8	2.7	0.8	0.5	0.5	0.9	---
10/26/89	4,420	354	1.56	74.0	67.8	60.0	7.8	5.1	1.9	0.8	---	---
11/1/89	3,650	357	1.23	61.0	176.3	124.0	52.3	42.9	5.7	2.4	1.2	---

(Sheet 3 of 9)

Table A2 (Continued)

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment ppm	Sieve Diameter Finer Than 0.062 mm ppm	Sieve Diameter Greater Than 0.062 mm ppm	Sand Very Fine 0.063 mm - 0.125 mm ppm	Sand Fine 1.250 mm - 0.250 mm ppm	Sand Medium 0.250 mm - 0.500 mm ppm	Sand Coarse 0.500 mm - 1.000 mm ppm	Sand Very Coarse 1.000 mm - 2.000 mm ppm
11/9/89	3,670	364	1.25	66.0	18.5	12.5	6.0	3.9	0.2	1.3	0.5	---
11/16/89	3,630	360	1.23	61.0	244.5	178.5	66.0	47.1	13.9	1.8	3.1	---
11/30/89	3,300	358	1.17	45.0	19.5	13.8	5.8	4.6	0.7	0.5	---	---
12/7/89	3,160	359	1.11	48.0	30.0	13.8	16.2	6.1	4.2	1.4	4.5	---
12/14/89	2,850	351	1.14	45.0	332.5	259.5	73.0	51.8	11.6	5.5	4.1	---
12/20/89	2,350	342	0.97	41.0	303.8	210.5	93.3	76.7	11.1	2.8	2.8	---
12/28/89	5,370	363	1.58	43.0	659.0	604.0	55.0	42.0	7.2	4.3	1.4	---
1/3/90	3,100	361	1.20	44.0	133.5	114.0	1935	12.4	7.1	---	---	---
1/11/90	1,450	341	0.75	48.0	429.0	280.8	148.2	88.2	45.9	8.9	5.2	---
1/18/90	1,830	346	0.88	49.0	147.3	89.5	54.8	41.3	6.9	3.3	3.3	---
2/15/90	38,430	513	4.11	51.0	219.2	196.7	22.5	16.0	3.0	3.0	0.5	---
2/21/90	35,900	505	4.02	50.0	194.7	172.2	22.5	20.6	1.9	---	---	---
3/1/90	21,320	503	2.80	51.0	289.3	171.6	117.7	89.4	12.6	12.6	3.1	---
3/8/90	14,100	492	2.11	53.0	240.5	180.5	60.0	50.7	7.6	1.6	---	---
3/13/90	64,000	516	5.33	57.0	488.8	391.0	97.8	93.9	2.3	1.6	---	---
3/17/90	83,300	534	6.04	58.0	589.3	519.8	69.5	62.3	7.2	---	---	---
3/22/90	90,000	546	6.43	60.0	1457.0	685.7	771.3	586.9	144.0	33.4	7.0	---
3/29/90	90,300	617	6.64	61.0	142.3	113.8	28.5	22.8	4.2	1.5	---	---
4/7/90	112,000	765	7.27	58.0	449.0	357.3	91.7	73.7	10.5	6.0	1.5	---
4/19/90	68,000	530	6.07	61.0	319.2	0.0	0.0	253.5	43.7	17.5	4.5	---
4/24/90	83,400	569	6.21	63.0	1099.0	1052.0	47.0	37.9	7.6	1.5	---	---
5/3/90	98,000	554	7.15	68.0	539.5	446.5	93.0	65.0	23.1	4.9	---	---
5/7/90	162,000	1600	6.61	67.0	3603.2	1566.2	2036.7	1213.9	633.4	189.4	---	---
5/8/90	186,000	1117	7.07	67.0	3802.3	1143.3	2659.0	2020.9	390.0	177.4	71.0	---

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Table A2 (Continued)

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment			Sand				
						Sieve Diameter		Very Fine 0.063 mm - 0.125 mm	Fine 1.250 mm - 0.250 mm	Medium 0.250 mm - 0.500 mm	Coarse 0.500 mm - 1.000 mm	Very Coarse 1.000 mm - 2.000 mm
					ppm	Finer Than 0.062 mm ppm	Greater Than 0.062 mm ppm	ppm	ppm	ppm	ppm	ppm
5/9/90	193,000	1119	6.87	68.0	2597.0	1219.2	1377.8	532.2	584.2	220.4	39.0	---
5/10/90	229,000	1200	6.92	67.0	1920.5	1021.0	967.0	446.8	346.2	160.0	13.5	---
5/11/90	257,000	1220	7.49	67.0	1728.7	869.2	859.5	573.3	157.3	119.5	9.5	---
5/12/90	253,000	1220	7.15	67.0	1491.8	682.5	809.2	365.0	261.4	163.5	19.4	---
5/13/90	244,000	1220	6.91	67.0	1505.7	674.7	830.7	386.3	320.8	99.8	23.7	---
5/14/90	211,000	1190	6.24	68.0	1026.5	506.8	519.7	313.5	139.8	56.7	9.3	---
5/15/90	185,000	1190	5.62	70.0	969.5	546.0	423.5	215.6	174.5	28.4	4.7	---
5/16/90	164,000	1180	5.45	72.0	919.0	539.8	379.2	215.0	140.3	23.9	---	---
5/17/90	136,000	1170	4.98	72.0	1063.5	666.7	396.8	236.0	126.9	29.4	4.5	---
5/18/90	126,000	1150	4.88	72.0	876.8	579.8	297.0	195.4	82.6	17.0	2.0	---
5/19/90	125,000	1150	4.79	70.0	979.0	655.8	323.0	218.7	88.0	16.2	---	---
5/21/90	125,000	832	4.83	71.0	690.0	421.7	268.3	153.7	91.2	17.4	5.9	---
6/12/90	78,900	594	5.09	72.0	874.3	437.0	437.0	302.0	63.4	55.5	15.7	---
6/14/90	77,900	591	5.23	71.0	205.0	125.0	80.0	53.8	17.9	7.1	1.2	---
6/22/90	75,700	587	5.11	76.0	184.2	132.2	52.0	34.1	9.8	6.8	1.3	---
7/5/90	21,800	505	2.68	82.0	415.5	255.0	160.5	103.2	34.4	19.1	3.8	---
7/13/90	3,530	360	1.41	81.0	42.0	26.0	16.0	14.2	1.8	---	---	---
7/26/90	4,840	436	0.89	86.0	67.5	27.5	40.0	36.7	3.3	---	---	---
8/10/90	15,700	499	2.33	85.0	326.2	194.0	132.2	125.6	6.6	---	---	---
8/24/90	6,260	381	1.37	85.0	100.5	22.2	78.2	56.5	17.6	4.1	---	---
9/13/90	4,830	406	0.97	82.0	---	---	---	---	---	---	---	---
9/21/90	4,300	381	0.95	84.0	57.5	16.8	40.7	34.7	4.9	1.1	---	---
9/27/90	24,100	502	3.54	80.0	363.0	151.2	211.5	108.7	35.9	32.0	34.9	---
10/5/90	5,170	424	1.03	78.0	256.0	37.0	219.0	201.7	17.3	---	---	---
10/18/90	31,400	533	4.80	69.0	292.0	176.5	115.5	2.2	11.7	35.0	66.6	---

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Table A2 (Continued)

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment ppm	Sieve Diameter Finer Than 0.062 mm ppm	Sieve Diameter Greater Than 0.062 mm ppm	Sand Very Fine 0.063 mm - 0.125 mm ppm	Sand Fine 1.250 mm - 0.250 mm ppm	Sand Medium 0.250 mm - 0.500 mm ppm	Sand Coarse 0.500 mm - 1.000 mm ppm	Sand Very Coarse 1.000 mm - 2.000 mm ppm
11/8/90	5,310	460	1.76	60.0	48.2	20.0	28.2	17.7	10.5	---	---	---
11/29/90	6,790	495	1.82	58.0	57.2	14.2	43.0	32.5	8.8	1.7	---	---
12/13/90	6,010	497	1.70	55.0	49.2	15.5	33.7	23.6	10.0	---	---	---
1/4/91	28,200	518	3.98	39.0	246.2	41.2	205.0	80.2	108.0	16.6	---	---
1/25/91	34,800	526	3.69	46.0	379.0	154.0	225.0	146.3	47.2	29.5	2.0	---
2/15/91	8,130	498	1.32	49.0	78.7	21.2	57.5	42.4	13.7	1.1	0.2	---
3/8/91	15,900	510	2.28	54.0	93.7	9.5	84.2	53.6	21.1	7.9	1.6	---
3/22/91	7,600	495	1.35	61.0	49.5	29.3	20.2	15.7	2.9	1.2	0.4	---
1/2/92	87,600	565	5.88	46.0	---	---	---	---	---	---	---	---
1/8/92	67,700	550	5.09	49.0	---	---	---	---	---	---	---	---
1/15/92	64,900	542	4.95	44.0	1300.2	554.7	745.5	427.9	267.0	44.8	5.6	---
1/22/92	59,300	538	4.98	42.0	1064.7	624.5	440.5	276.5	133.0	24.0	7.2	---
1/28/92	50,800	535	4.75	44.0	501.7	263.5	238.2	155.8	58.4	16.2	7.8	---
2/4/92	24,800	502	3.24	48.0	432.0	237.5	194.5	139.4	46.7	6.9	1.5	---
2/11/92	18,800	467	2.77	48.0	356.0	182.8	173.2	138.2	34.6	0.4	---	---
2/20/92	42,700	531	4.41	51.0	261.0	144.0	117.0	77.6	32.4	6.3	0.7	---
2/25/92	34,000	525	3.92	50.0	336.0	187.3	148.7	99.2	44.2	5.3	---	---
3/4/92	29,200	524	3.68	---	494.0	229.5	264.5	180.0	67.2	17.3	---	---
3/11/92	78,000	555	6.09	52.0	793.7	446.0	347.7	305.3	37.7	4.1	0.6	---
3/18/92	37,500	534	3.75	58.0	353.0	165.8	187.2	148.9	23.9	12.0	2.4	---
3/25/92	38,700	531	3.69	53.0	193.5	111.5	82.0	70.8	10.2	1.0	---	---
4/2/92	17,000	515	2.26	56.0	252.7	115.7	137.0	114.8	19.4	2.8	---	---
4/10/92	10,500	507	1.66	64.0	161.0	115.2	45.8	42.9	2.6	0.2	---	---

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Table A2 (Continued)

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment ppm	Suspended Sediment, Sieve Diameter: Finer Than 0.062 mm ppm	Suspended Sediment, Sieve Diameter: Greater Than 0.062 mm ppm	Sand: Very Fine 0.063 mm - 0.125 mm ppm	Sand: Fine 1.250 mm - 0.250 mm ppm	Sand: Medium 0.250 mm - 0.500 mm ppm	Sand: Coarse 0.500 mm - 1.000 mm ppm	Sand: Very Coarse 1.000 mm - 2.000 mm ppm
4/13/92	8,940	503	1.49	68.0	123.7	99.0	24.7	16.9	7.1	0.7	---	---
4/20/92	10,000	504	1.60	71.0	222.5	133.5	89.0	50.8	31.5	5.7	0.9	---
4/27/92	23,800	519	2.93	68.0	383.7	168.7	215.0	129.0	64.0	20.1	1.9	---
5/5/92	34,600	528	3.90	72.0	232.7	129.7	102.0	60.5	27.4	12.6	1.5	---
5/18/92	14,400	512	2.27	79.0	336.8	234.3	102.5	41.5	37.9	19.4	3.7	---
5/26/92	33,000	426	4.07	77.0	407.7	214.2	193.7	107.5	70.2	15.0	1.0	---
6/19/92	69,300	550	5.41	82.0	730.2	228.2	502.0	410.1	62.5	25.4	4.0	---
6/24/92	49,600	543	4.24	76.0	930.0	366.5	563.5	445.2	93.5	21.2	3.6	---
6/30/92	51,800	543	4.47	73.0	826.0	398.8	427.2	316.6	90.1	18.6	1.9	---
7/10/92	37,300	532	3.69	80.0	539.7	231.2	308.5	243.5	58.1	5.2	1.7	---
7/13/92	20,900	517	2.61	82.0	622.7	196.0	426.7	330.7	72.5	20.1	3.4	---
7/20/92	53,100	538	4.66	77.0	1125.7	441.0	684.7	386.8	234.8	49.8	13.4	---
7/28/92	21,100	519	2.74	82.0	368.0	169.5	198.5	154.8	38.1	3.9	1.6	---
8/7/92	29,100	528	3.29	79.0	343.3	254.8	88.5	0.4	4.3	36.5	47.3	---
8/13/92	26,600	526	3.17	78.0	535.8	355.5	180.3	109.4	61.3	9.0	0.6	---
8/20/92	10,800	493	1.86	75.0	176.2	89.0	87.2	72.0	14.1	1.1	---	---
8/24/92	8,580	477	1.53	78.0	108.7	80.5	28.2	23.9	3.7	0.7	---	---
9/3/92	8,310	469	1.59	74.0	157.3	48.7	109.0	99.3	9.7	---	---	---
9/11/92	22,800	517	3.11	72.0	346.5	179.2	167.3	96.7	36.7	22.2	11.7	---
9/17/92	18,500	515	2.67	78.0	394.7	221.0	173.7	89.1	59.2	19.3	6.1	---
9/25/92	45,300	536	4.70	68.0	1590.5	589.3	1001.2	356.4	434.5	90.1	120.1	---
10/1/92	22,300	517	3.22	63.0	211.7	179.0	32.7	24.2	5.6	2.3	0.6	---
10/22/92	4,650	461	1.33	63.0	42.2	34.0	8.2	6.7	1.0	0.5	---	---
11/4/92	3,950	455	1.14	60.0	63.0	42.0	21.0	19.5	1.5	---	---	---
12/3/92	34,000	526	4.45	45.0	1066.7	758.7	308.0	165.7	55.4	56.4	30.5	---
12/22/92	98,900	587	7.01	46.0	674.2	192.6	481.6	371.8	56.8	35.1	17.3	---

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Table A2 (Continued)

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment			Sand				
						Sieve Diameter		Very Fine 0.063 mm - 0.125 mm ppm	Fine 1.250 mm - 0.250 mm ppm	Medium 0.250 mm - 0.500 mm ppm	Coarse 0.500 mm - 1.000 mm ppm	Very Coarse 1.000 mm - 2.000 mm ppm
					ppm	Finer Than 0.062 mm ppm	Greater Than 0.062 mm ppm					
1/6/93	53,100	547	4.50	46.0	231.7	52.7	179.0	144.1	23.1	8.9	2.9	---
1/27/93	46,100	543	4.30	45.0	127.5	53.0	74.5	57.1	5.6	7.0	4.8	---
2/18/93	64,800	548	5.89	45.0	202.7	156.5	46.2	27.6	7.5	8.9	2.2	---
3/25/93	54,300	542	5.02	52.0	575.7	165.0	410.7	277.6	58.7	58.7	15.7	---
1/19/94	18,900	515	2.49	43.0	61.0	33.5	27.5	18.3	6.9	2.3	---	---
2/7/94	21,400	520	2.71	49.0	192.7	96.0	96.7	84.5	8.1	4.1	---	---
2/23/94	16,600	505	2.44	53.0	128.0	65.0	63.0	48.1	14.9	---	---	---
3/16/94	51,400	547	4.51	52.0	529.5	227.5	302.0	120.8	96.0	85.2	---	---
4/5/94	9,400	465	1.74	59.0	120.7	67.7	53.0	35.4	9.8	6.7	1.1	---
5/3/94	35,300	557	4.20	61.0	2688.0	2589.5	98.5	15.9	30.7	49.6	2.3	---
6/17/94	21,000	512	2.96	80.0	198.0	148.0	50.0	7.3	22.6	19.4	0.7	---
7/7/94	6,200	485	1.41	84.0	148.0	105.3	42.6	30.1	9.5	2.2	0.8	---
7/26/94	16,200	508	2.61	83.0	131.7	96.7	35.0	21.5	12.1	1.4	---	---
10/19/94	3,900	445	1.22	65.0	---	---	---	---	---	---	---	---
11/15/94	46,800	535	5.38	60.0	350.0	188.0	162.0	119.9	34.5	7.3	0.3	---
12/7/94	16,400	508	2.52	55.0	144.0	31.0	113.0	97.0	16.0	---	---	---
1/19/95	47,600	538	4.77	49.0	355.5	225.8	129.7	67.1	54.2	8.4	---	---
2/13/95	13,700	510	2.06	46.0	131.5	78.8	52.7	45.0	7.3	0.4	---	---
3/3/95	13,200	508	2.04	51.0	144.2	136.2	8.0	5.7	2.1	0.1	---	---
3/22/95	41,500	536	4.26	58.0	675.2	341.2	334.0	218.4	81.5	33.8	---	---
4/11/95	44,800	538	4.62	63.0	791.5	412.2	379.2	245.7	115.7	17.8	---	---
4/26/95	45,300	534	4.61	62.0	757.7	416.5	341.2	9.8	44.7	251.5	35.2	---
5/12/95	86,100	560	6.33	67.0	1035.5	378.5	657.0	392.2	141.9	116.3	6.6	---

(Sheet 8 of 9)

Table A2 (Concluded)

Date	Streamflow, Instantanous cfs	Total Width ft	Mean Velocity fps	Water Temperature F	Suspended Sediment ppm	Sieve Diameter Finer Than 0.062 mm ppm	Sieve Diameter Greater Than 0.062 mm ppm	Sand Very Fine 0.063 mm - 0.125 mm ppm	Sand Fine 1.250 mm - 0.250 mm ppm	Sand Medium 0.250 mm - 0.500 mm ppm	Sand Coarse 0.500 mm - 1.000 mm ppm	Sand Very Coarse 1.000 mm - 2.000 mm ppm
6/2/95	49,100	544	4.27	73.0	1153.5	481.3	672.2	463.8	148.6	57.8	2.0	---
6/22/95	56,300	543	4.65	78.0	894.2	255.2	639.0	546.3	89.5	3.2	---	---
7/13/95	26,400	526	3.29	84.0	443.2	57.0	386.2	347.6	38.6	---	---	---
7/26/95	9,610	506	1.83	85.0	115.0	65.8	49.2	38.2	11.0	---	---	---
8/16/95	40,800	534	4.64	84.0	921.7	321.5	600.2	503.6	87.0	9.6	---	---
8/30/95	10,000	508	2.01	84.0	158.7	91.0	67.7	46.6	18.6	2.2	0.3	---
9/20/95	9,930	506	2.08	76.0	125.7	70.2	55.5	47.4	6.4	1.7	---	---
10/11/95	11,200	506	2.37	74.0	301.5	175.8	125.7	76.4	29.3	16.2	3.8	---
10/30/95	3,620	451	1.23	61.0	134.0	101.7	32.3	20.8	5.8	4.4	1.3	---
12/12/95	3,230	450	1.13	44.0	44.0	34.0	10.0	6.1	2.2	1.7	---	---
1/3/96	6,840	495	1.98	44.0	63.0	59.0	4.0	2.4	1.6	---	---	---
1/23/96	10,800	509	2.60	44.0	---	---	---	---	---	---	---	---
2/13/96	6,090	495	1.93	47.0	103.5	30.3	73.2	50.8	17.2	5.2	---	---
3/4/96	5,520	493	1.77	54.0	404.2	235.5	168.7	96.1	33.9	25.8	13.0	---
3/19/96	3,260	437	1.34	54.0	141.0	99.5	41.5	22.0	9.8	6.8	2.9	---
5/13/96	18,300	522	3.29	72.0	72.0	65.0	7.0	3.9	2.7	0.4	---	---
6/4/96	8,180	499	1.98	78.0	157.2	131.5	25.7	17.0	7.4	1.3	---	---
6/19/96	10,000	501	2.22	80.0	252.5	133.0	119.5	60.0	39.0	17.2	3.3	---
7/2/96	5,350	495	1.55	82.0	63.0	40.7	22.3	21.3	1.0	---	---	---
7/25/96	13,200	514	2.74	82.0	107.7	65.5	42.2	32.3	8.1	1.8	---	---
8/13/96	15,900	516	2.90	81.0	271.7	194.7	77.0	21.4	29.0	25.6	1.0	---
9/3/96	24,100	532	3.69	76.0	271.2	173.5	97.7	48.1	28.7	14.8	6.1	---

(Sheet 9 of 9)

Table A3
Reach Bank Samples, Arthur City, TX

Sample Number	RS001	RS002	RS003	RS004	RS019	RS020	RS030	RS035	RS039
River Mile	629.8	629.8	629.8	629.8	630.7	631.5	631.5	632.1	632.1
Cross Section Number	1	1	1	1	2	3	3	5	5
Looking Downstream	left	left	left	left	right	left	right	left	right
Percent finer by volume									
5	3.41	4.37	3.32	0.96	3.03	1.71	2.78	2.37	0.89
10	11.60	21.32	14.49	1.59	10.66	3.57	7.92	5.47	1.37
15	23.60	32.28	24.98	2.52	22.38	6.41	19.54	10.77	1.94
20	33.32	39.61	32.33	3.82	32.11	11.46	30.77	18.99	2.61
25	41.44	45.30	38.20	5.61	40.89	19.71	39.23	27.53	3.39
30	48.51	50.18	43.29	8.05	49.18	28.73	46.24	35.38	4.34
35	54.75	54.54	47.88	11.19	57.02	37.41	52.54	42.61	5.52
40	60.50	58.58	52.15	14.90	64.41	45.51	58.38	49.45	7.02
45	65.96	62.38	56.22	18.95	71.49	53.03	64.01	56.15	8.94
50	71.30	66.08	60.22	23.26	78.44	60.06	69.55	62.92	11.40
55	76.64	69.76	64.18	27.74	85.42	66.82	75.15	70.00	14.33
60	82.18	73.55	68.19	32.41	92.58	73.52	80.95	77.73	17.60
65	88.06	77.45	72.40	37.43	100.20	80.36	87.07	86.52	21.05
70	94.41	81.67	76.76	43.07	108.60	87.60	93.63	97.11	24.74
75	101.40	86.31	81.74	49.92	118.00	95.58	100.90	110.80	28.88
80	109.90	91.40	87.41	58.68	129.30	104.90	109.50	132.50	33.74
85	120.40	97.90	94.12	70.81	143.40	116.60	120.10	173.10	39.99
90	135.30	106.20	103.00	88.26	163.60	133.40	134.70	233.60	49.60
95	163.00	119.10	117.60	116.10	203.60	178.70	161.50	313.70	72.36

(Continued)

Table A3 (Concluded)									
Sample Number	RS040	RS048	RS055	RS065	RS066	RS071	Diameter, mm		
River Mile	633.9	634.8	634.8	635.6	636.6	636.6			
Cross Section									
Number	6	7	7	9	10	10			
Looking									
Downstream	left	left	right	left	right	left	Average	Maximum	Minimum
Percent finer by									
volume									
5	1.79	1.10	10.29	2.24	2.18	4.30	0.003	0.010	0.001
10	3.62	1.94	37.50	5.15	6.11	19.10	0.010	0.038	0.001
15	6.00	3.14	53.62	10.39	12.95	35.96	0.018	0.054	0.002
20	9.24	4.86	65.72	19.73	19.94	47.62	0.025	0.066	0.003
25	13.55	7.36	75.81	30.43	25.86	56.69	0.031	0.076	0.003
30	18.68	10.94	84.74	40.49	31.24	64.31	0.038	0.085	0.004
35	24.23	15.39	93.16	49.41	36.39	71.03	0.044	0.093	0.006
40	30.14	20.03	101.40	57.38	41.50	77.29	0.049	0.101	0.007
45	36.48	24.64	109.90	64.67	46.73	83.28	0.055	0.110	0.009
50	43.20	29.30	119.00	71.62	52.00	89.22	0.061	0.119	0.011
55	50.28	34.04	128.80	78.51	58.08	95.29	0.066	0.129	0.014
60	57.69	38.89	139.70	85.56	64.61	101.50	0.072	0.140	0.018
65	65.70	43.90	152.00	93.04	72.03	108.30	0.079	0.152	0.021
70	74.50	49.23	166.10	101.30	80.73	115.70	0.086	0.166	0.025
75	84.62	55.06	182.70	111.00	91.27	124.00	0.095	0.183	0.029
80	97.28	61.72	203.10	123.40	105.20	133.70	0.105	0.203	0.034
85	114.70	69.82	229.10	141.70	124.30	146.60	0.120	0.229	0.040
90	145.30	81.42	264.80	181.40	154.70	166.50	0.143	0.265	0.050
95	334.00	102.80	318.80	406.70	224.40	222.90	0.204	0.407	0.072

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

A numerical model study was conducted to evaluate the effect that reducing bank erosion between Arthur City, TX, and Index, AR, would have on deposition rates in the J. Bennett Johnston (Red River) Waterway. This was accomplished by evaluating measured sediment data and by using the HEC-6W numerical sedimentation model. Deposition rates in the navigation pool upstream from Joe D. Waggonner Jr. Lock and Dam (Lock and Dam No. 5) were predicted for existing bank erosion conditions, and for conditions where existing bank erosion was reduced by 50 and 100 percent.

15. SUBJECT TERMS

Bank erosion	Numerical model	Sedimentation
HEC-6	Red River	

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